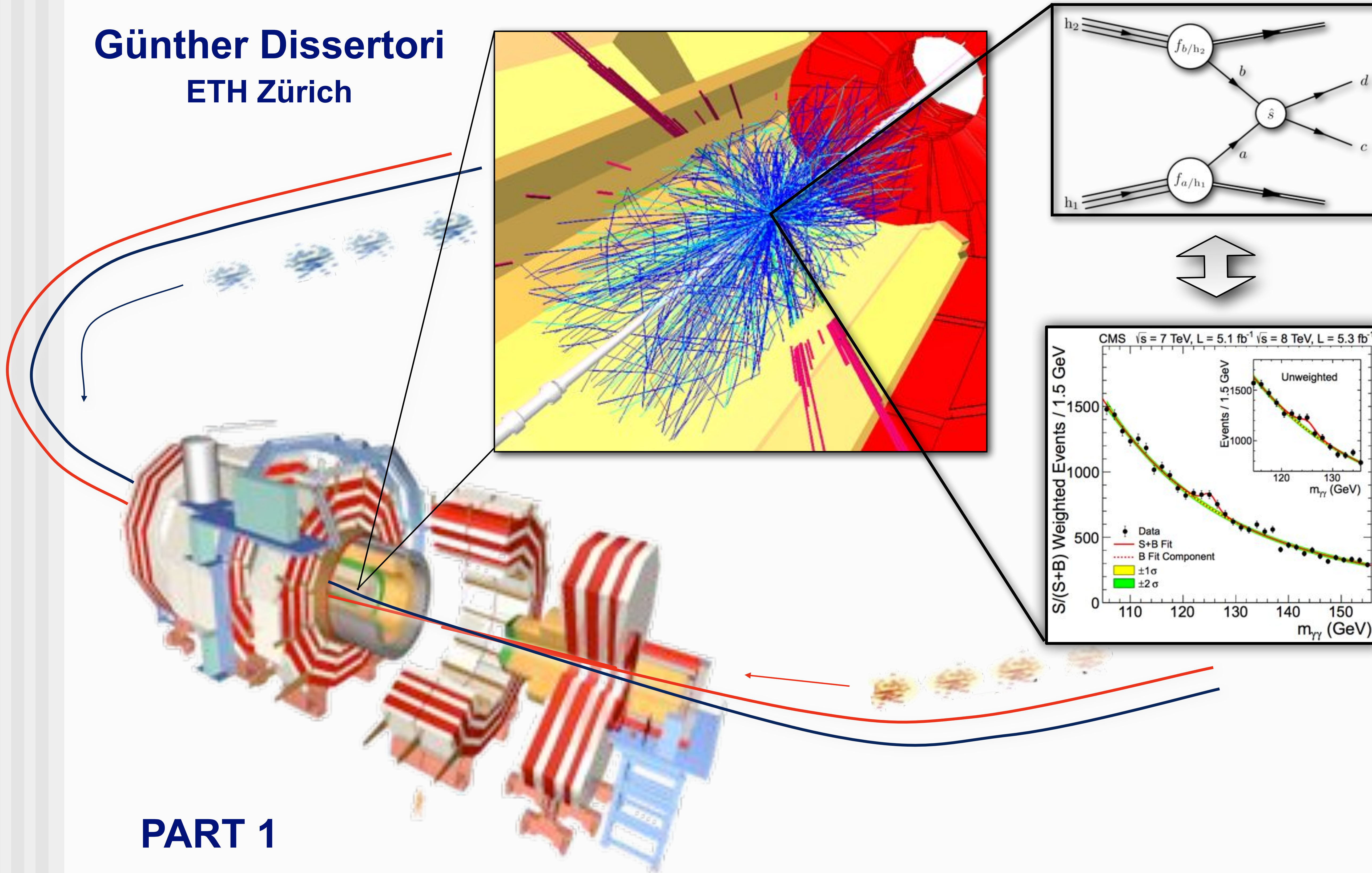
Experimental Results from CMS

ETH Institute for Particle Physics

Günther Dissertori

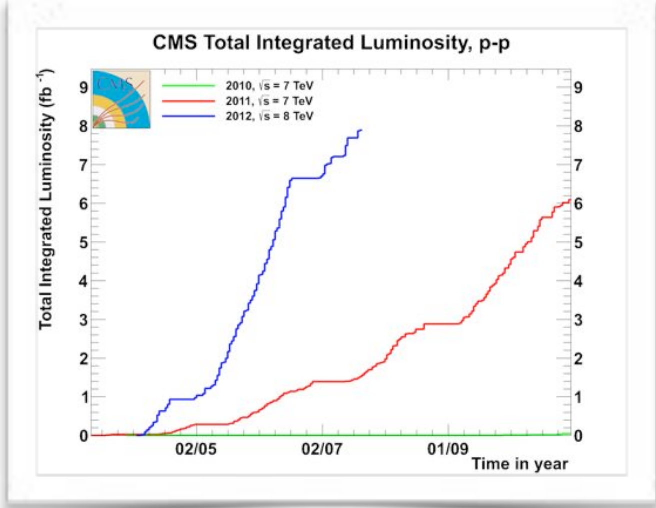
ETH Zürich

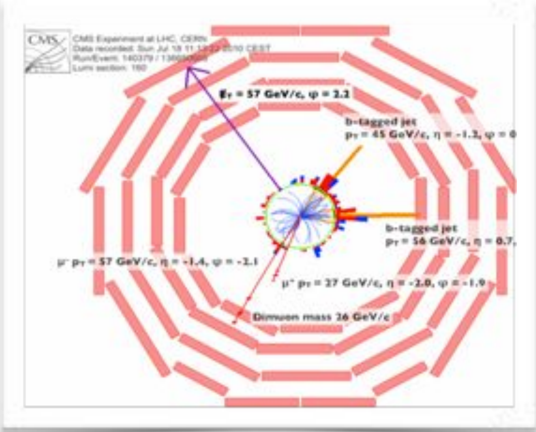


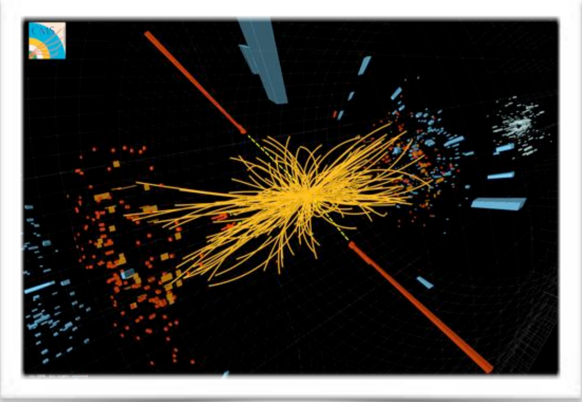
PART 1

Overall Outline

- Introduction
  - CMS, Lumi, performance
- SM Physics
  - QCD, EWK, TOP
- BSM Physics
  - some Exotica and SUSY searches
- Searches for the Higgs







- Bonus Material (only in backup)
  - Machine
  - Physics expectations,requirements
  - Tools/Methods

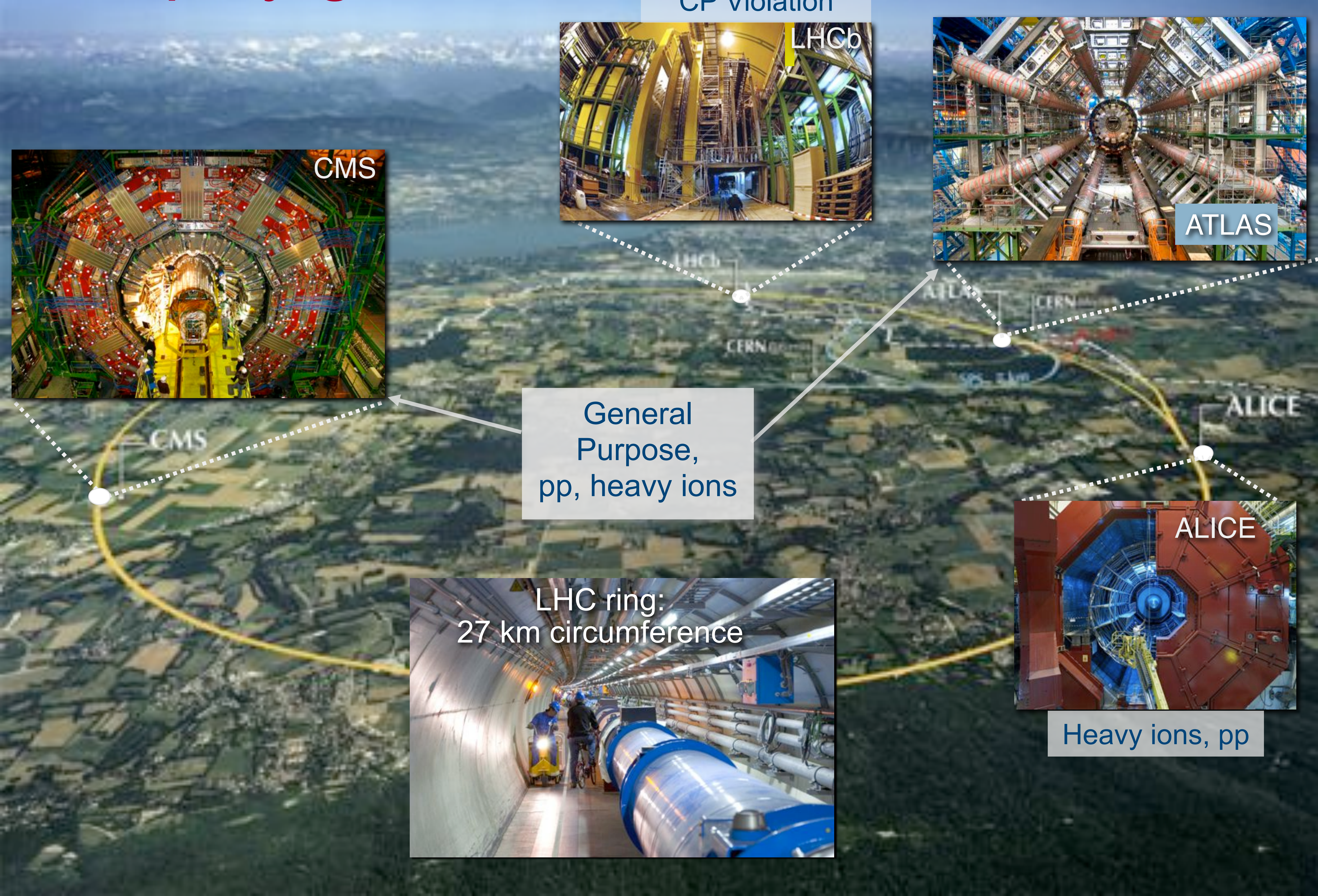
Disclaimer 1 : Many introductory and theoretical aspects covered in the other lectures

Disclaimer 2 : For complete list of results: see https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

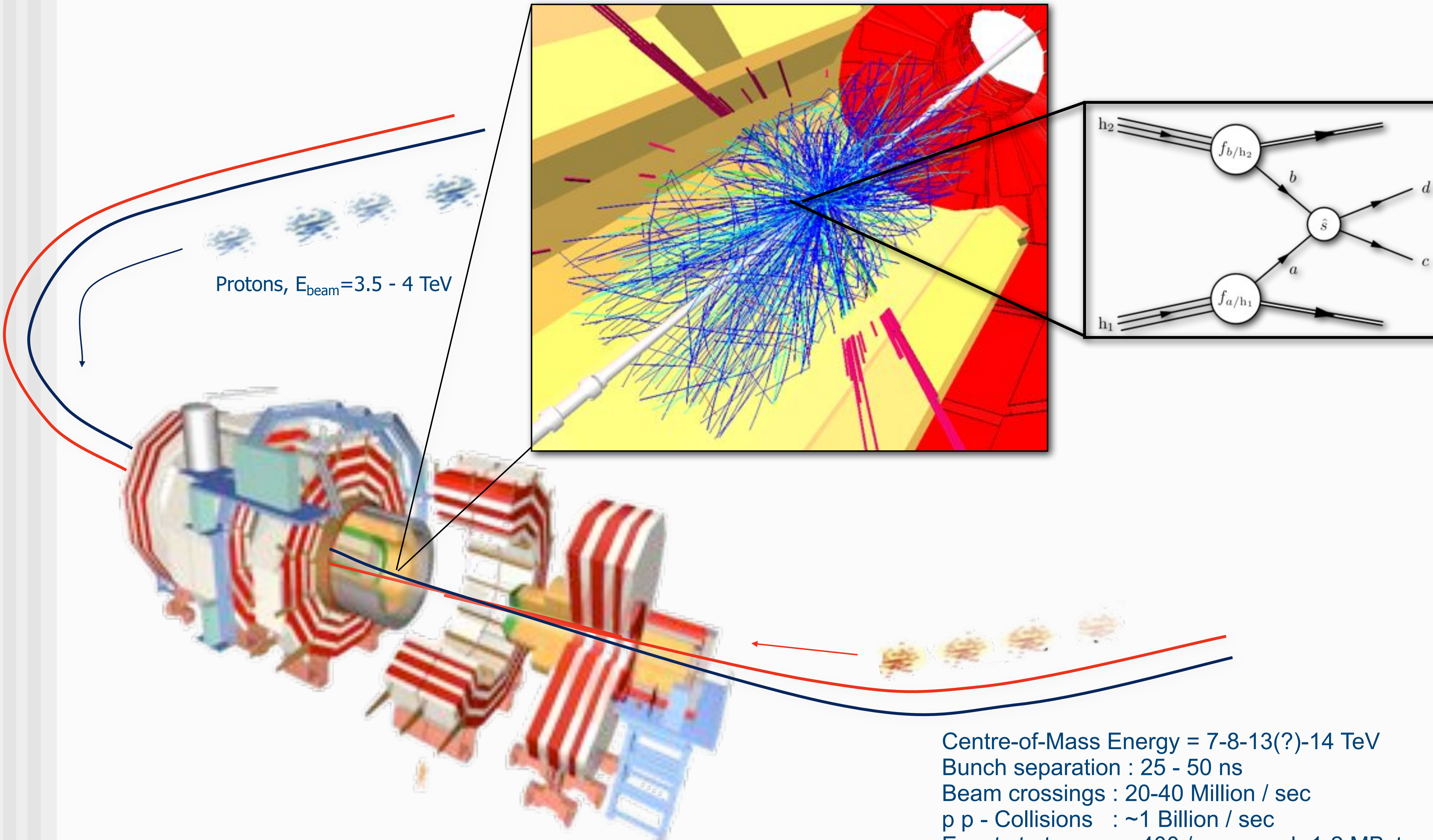
Disclaimer 3 : Some slides or slide content taken from seminars/lectures/write-ups of other colleagues or previous lectures of mine

Introduction

Our play ground



Collisions at the LHC

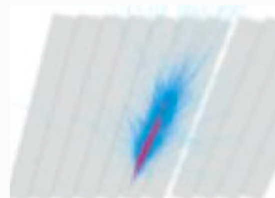


Centre-of-Mass Energy = 7-8-13(?)-14 TeV
Bunch separation : 25 - 50 ns
Beam crossings : 20-40 Million / sec
p p - Collisions : ~1 Billion / sec
Events to tape : ~400 / sec, each 1-2 MByte

Compact Muon Solenoid

Superconducting Coil 3.8 Tesla

CALORIMETERS

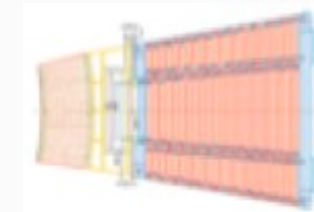


ECAL

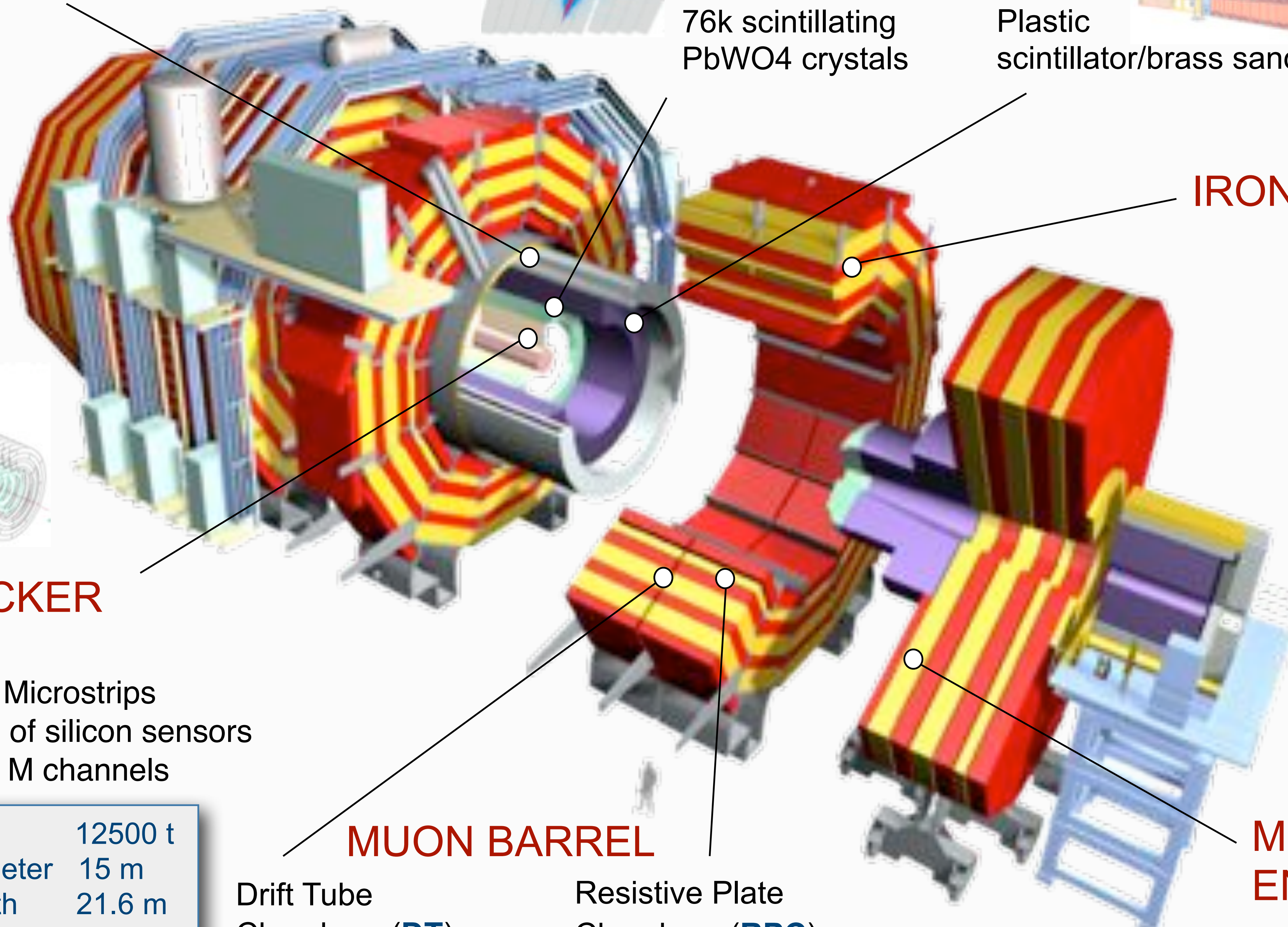
76k scintillating PbWO4 crystals

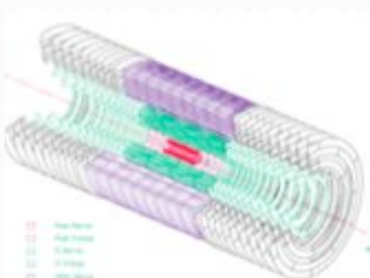
HCAL

Plastic scintillator/brass sandwich



IRON YOKE





TRACKER

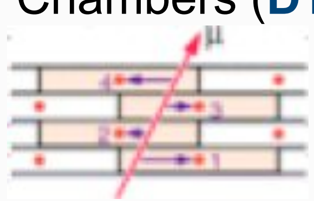
Pixels
Silicon Microstrips
210 m² of silicon sensors
66+9.6 M channels

Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

>3000 scientists from
179 Institutes from
41 countries

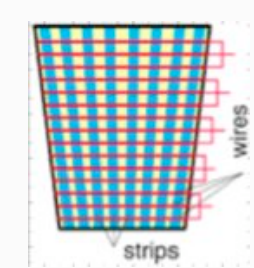
MUON BARREL

Drift Tube Chambers (**DT**)



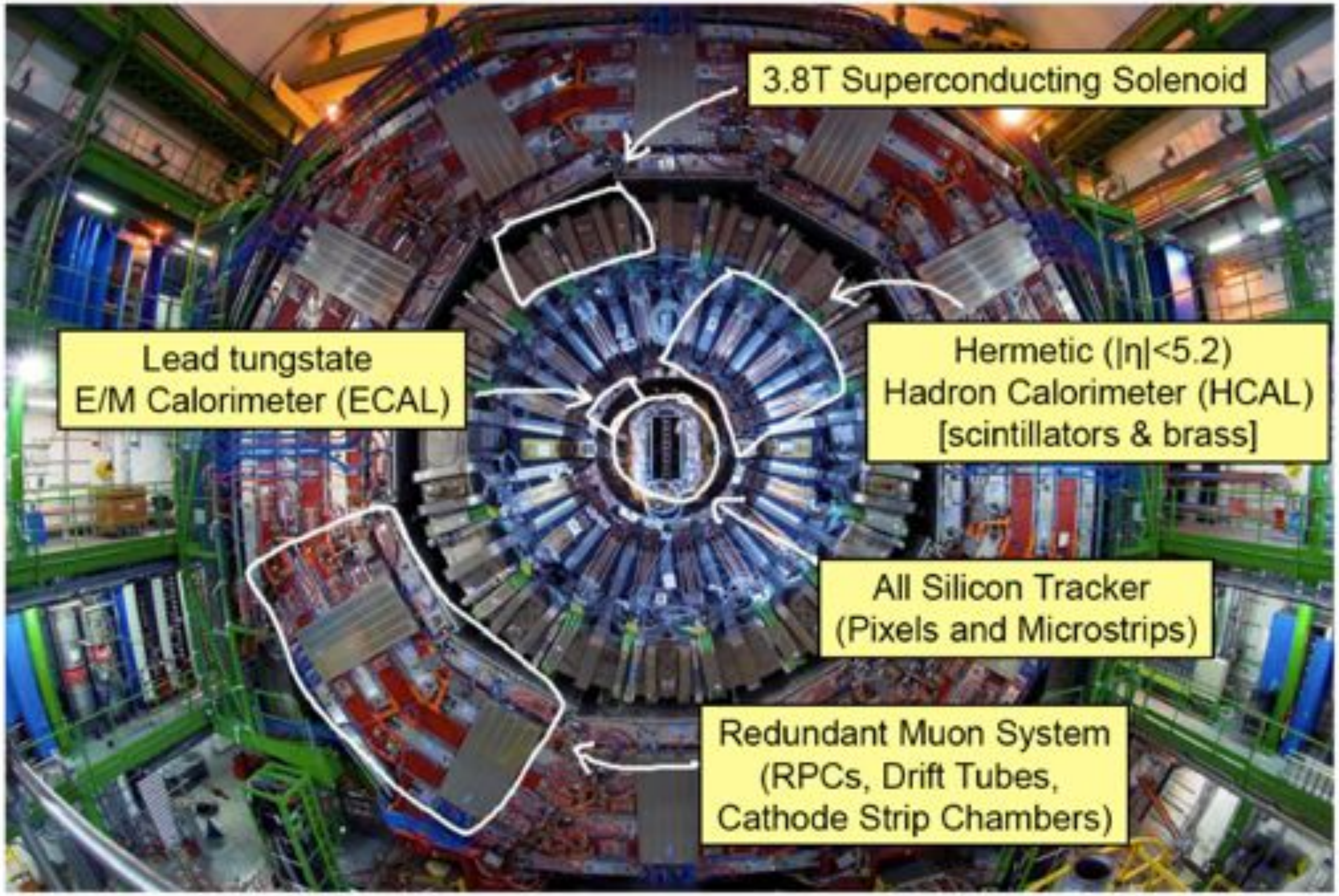
Resistive Plate Chambers (**RPC**)

MUON ENDCAPS



Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

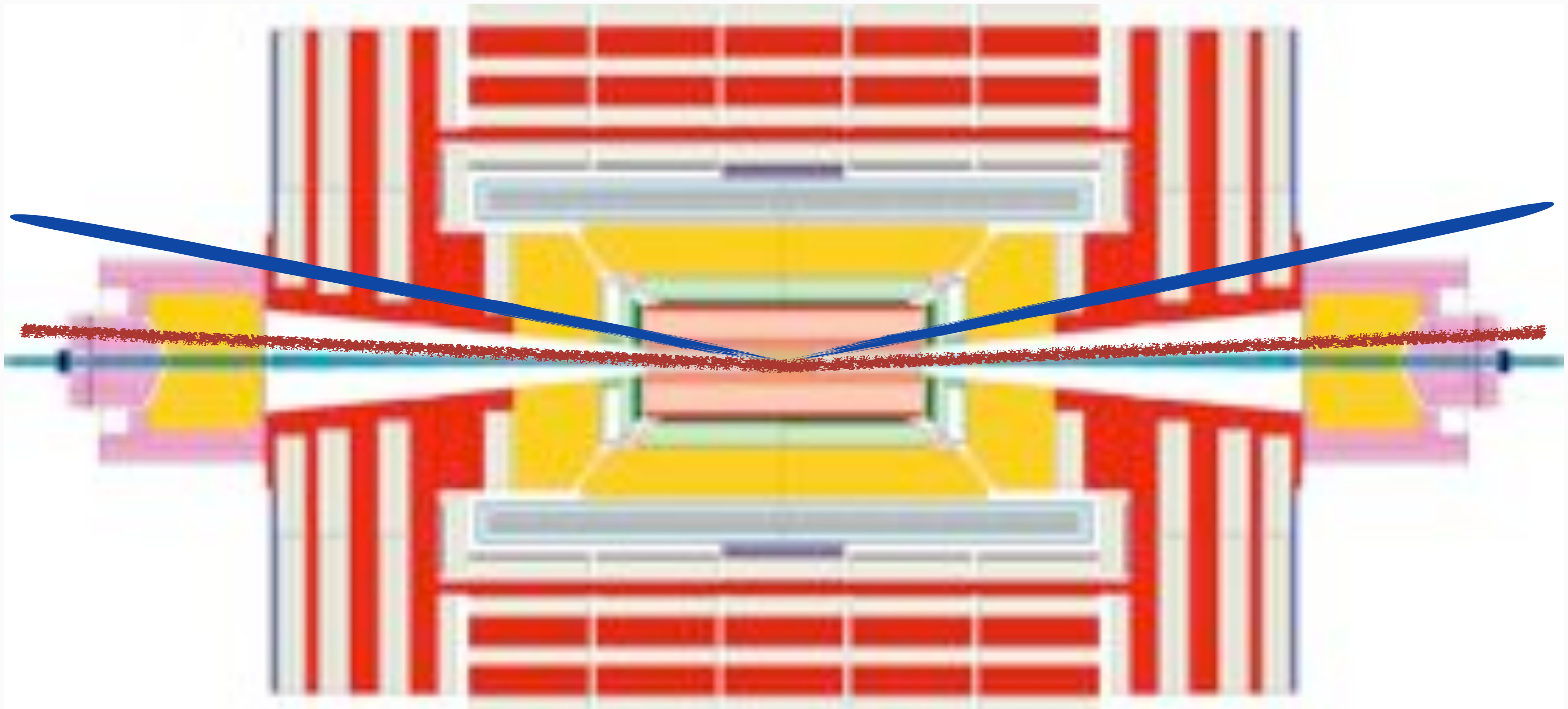
CMS: another view



To remember:

- only one magnet
- very large B field
- large Si tracking system
- very high resolution, very granular ECAL
- ECAL and HCAL inside solenoid
- Muon system embedded in iron return yoke

Typical detector acceptance



- Precision tracking and **lepton** reconstruction up to rap~2.5
  - p_T thresholds for tracks ~ 100 MeV, for leptons 10-20 GeV
- **Jet and MET** reconstruction: include detectors up to rap~4.5-5
  - p_T thresholds for jets ~30 GeV, if tracking-based jets ~15 GeV

Performance, Object reconstruction

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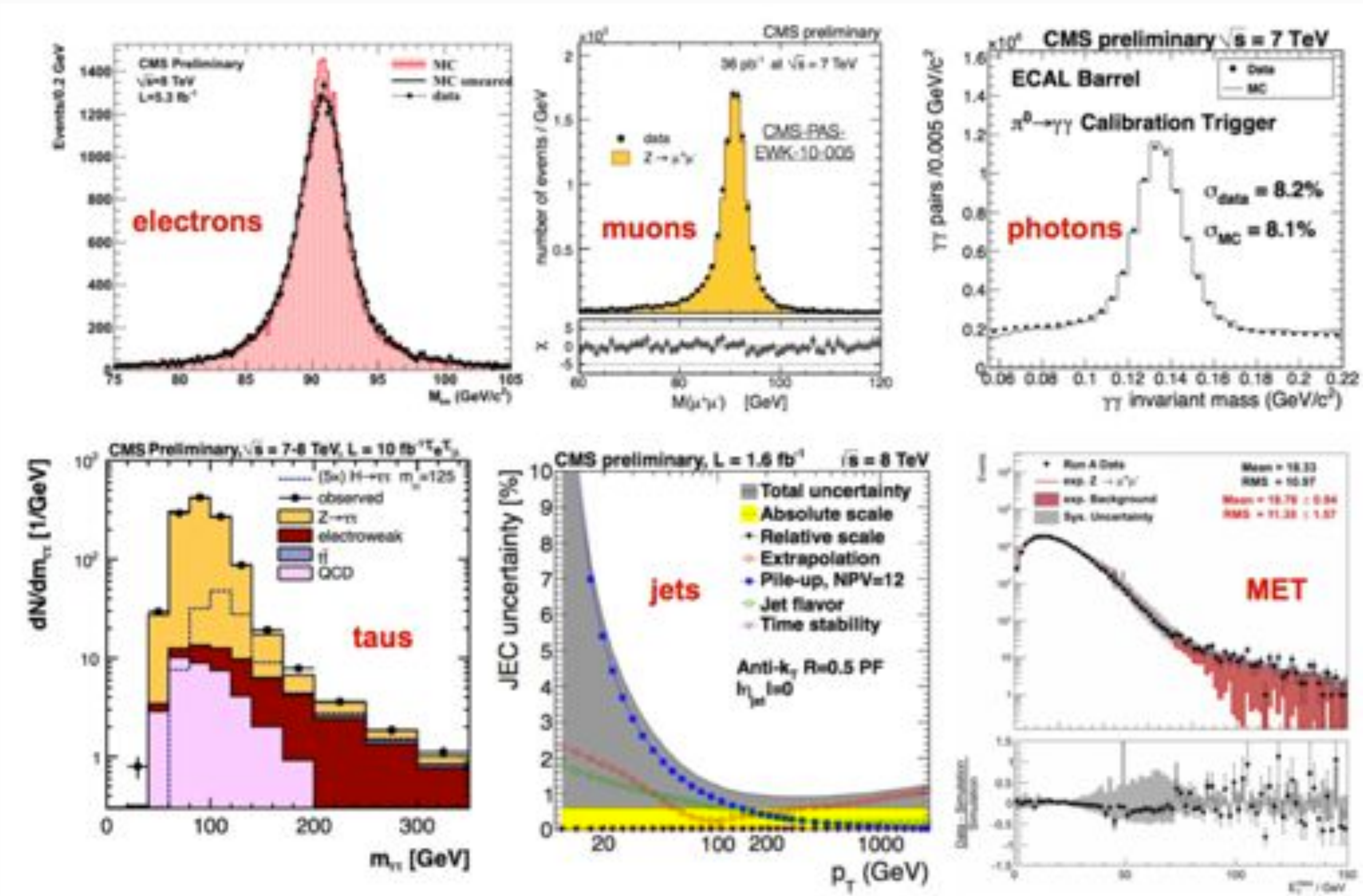
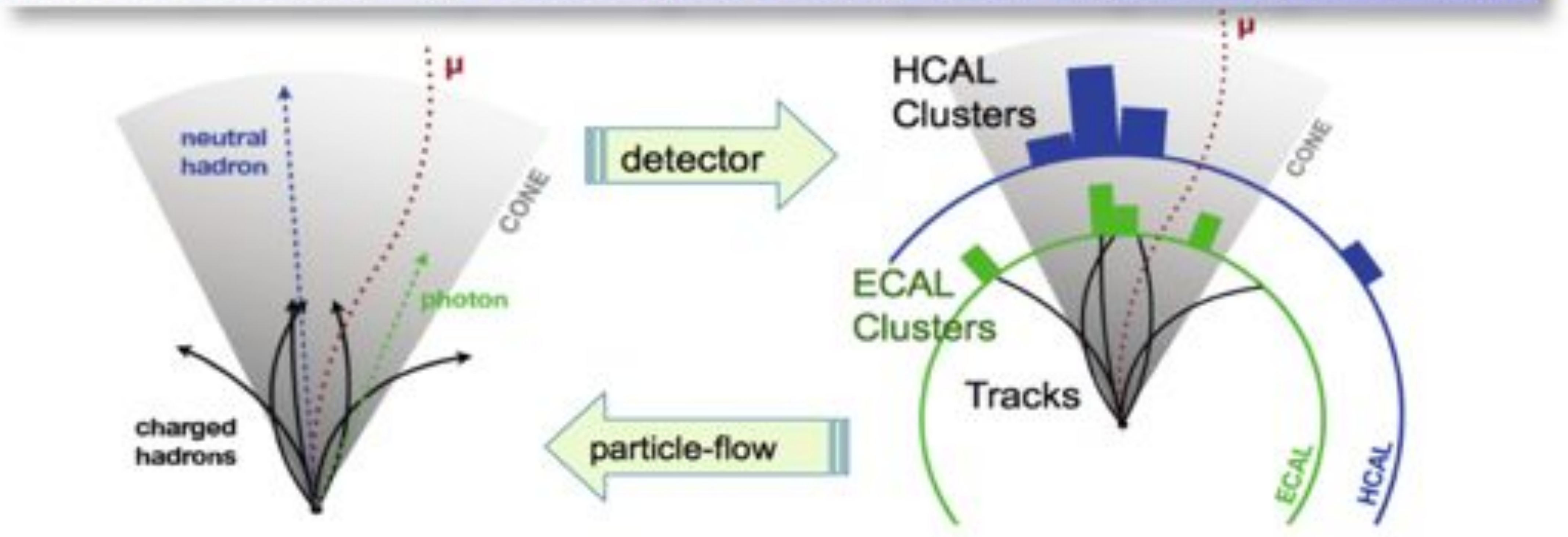


- By now, **Particle Flow algorithm** has become a central tool (see next)
- non-showering electrons in barrel: resolution (reconstructed Z peak) close to 1 GeV
- muon momentum resolution: 1% for p_T < 100 GeV, 7-8% at 1 TeV
- pions mis-ID as muons: <0.5% for p_T > 2 GeV
- Tau ID eff. > 65% for p_T > 20 GeV, with mis-ID eff. of hadronic jets < 3%
- b-jet tagging eff. of 70% for p_T > 30 GeV, with mis-ID eff. of light-quark jets < 3%

Global Event Description (Pflow)

Made possible by CMS granularity and high magnetic field



- Charged particles well separated in large tracker volume & 3.8T B field
- Excellent tracking, able to go to down to very low momenta (~100 MeV)
- Granular electromagnetic calorimeter with excellent energy resolution
- In multi-jet events, only 10% of the energy goes to neutral (stable) hadrons (~60% charged, ~30% neutral electromagnetic)
- Therefore: **Use a global event description** :
  - Optimal combination of information from all subdetectors
  - Returns a list of reconstructed particles (e,mu,photons,charged and neutral hadrons)
  - Used in the analysis as if it came from a list of generated particles
  - Used as building blocks for jets, taus , missing transverse energy , isolation and PU particle ID

Particle Flow performance

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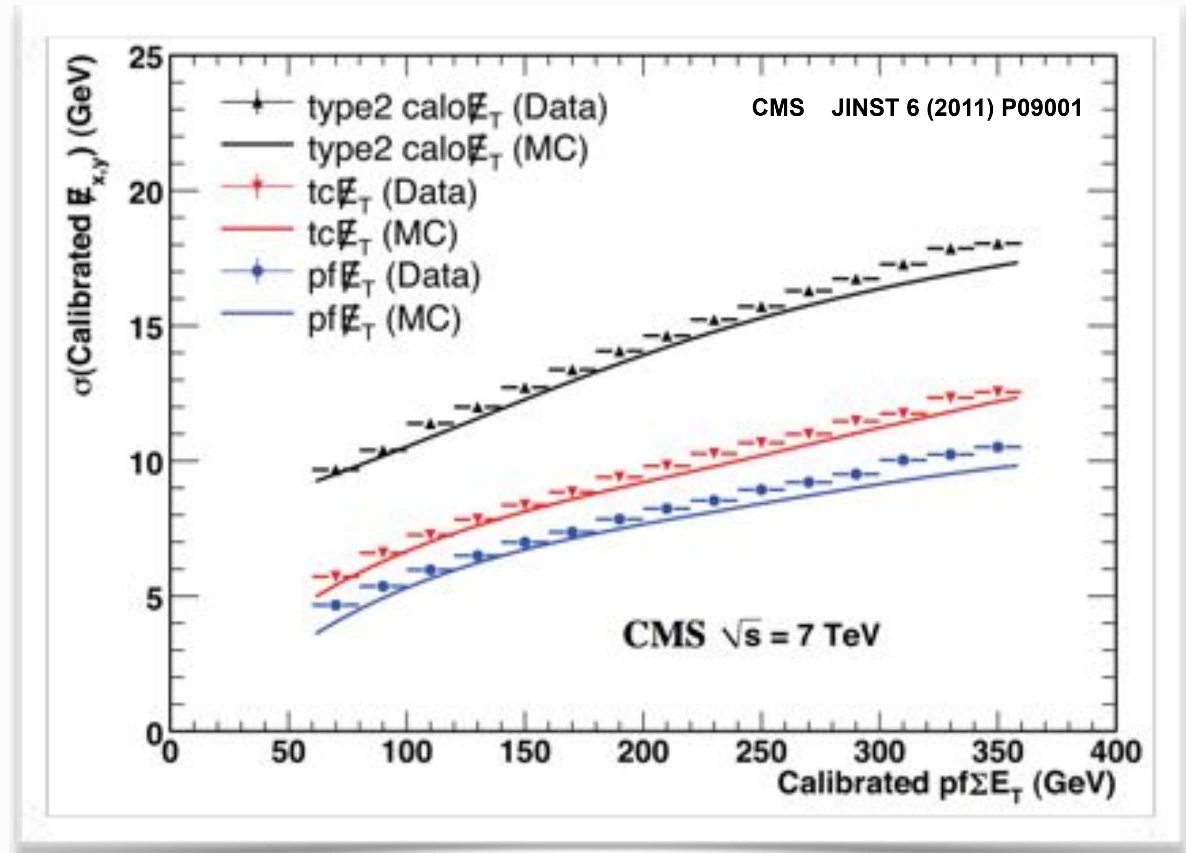
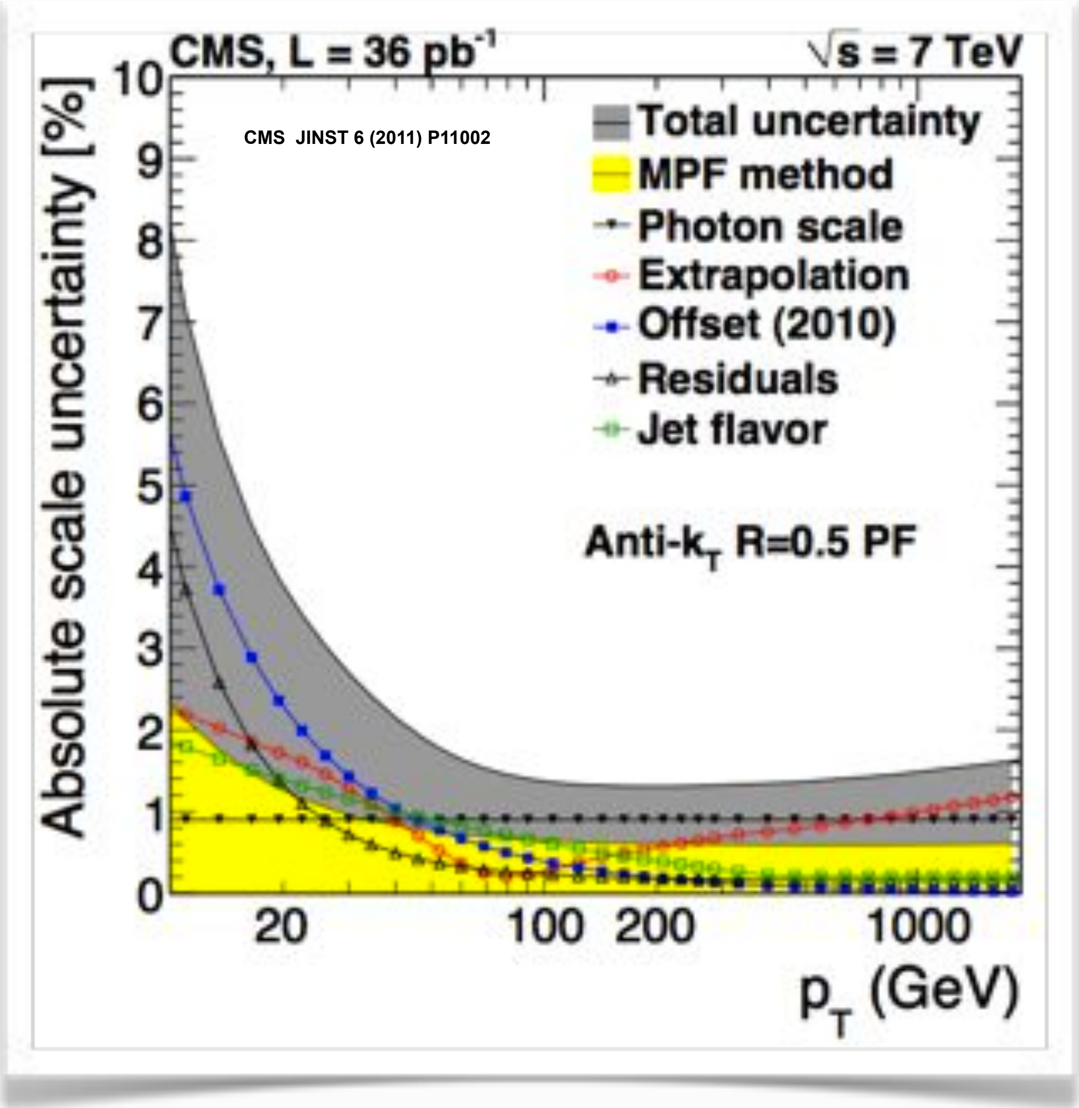
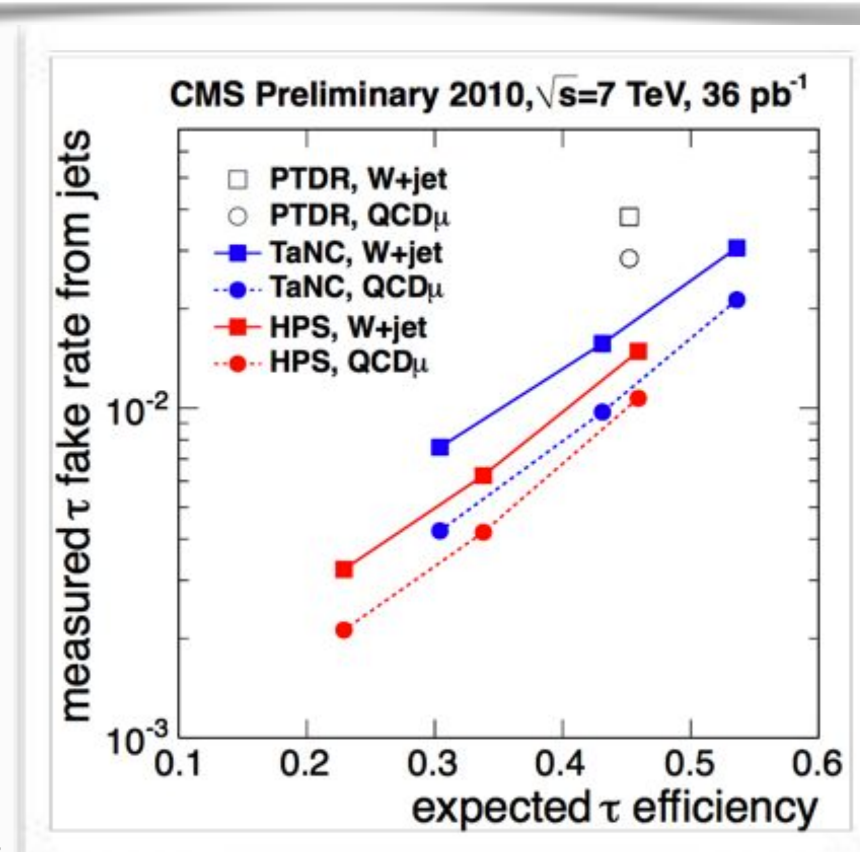
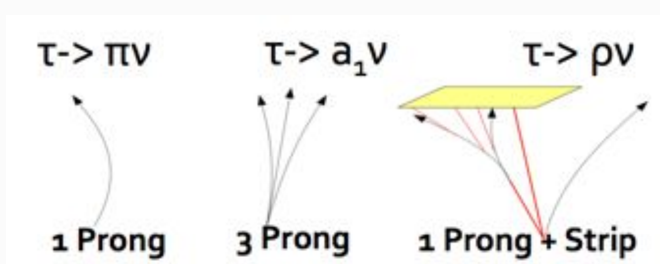
- Considerable improvement in Jet Energy scale uncertainty and jet/MET resolution, as well as tau identification:









Integrated Luminosity

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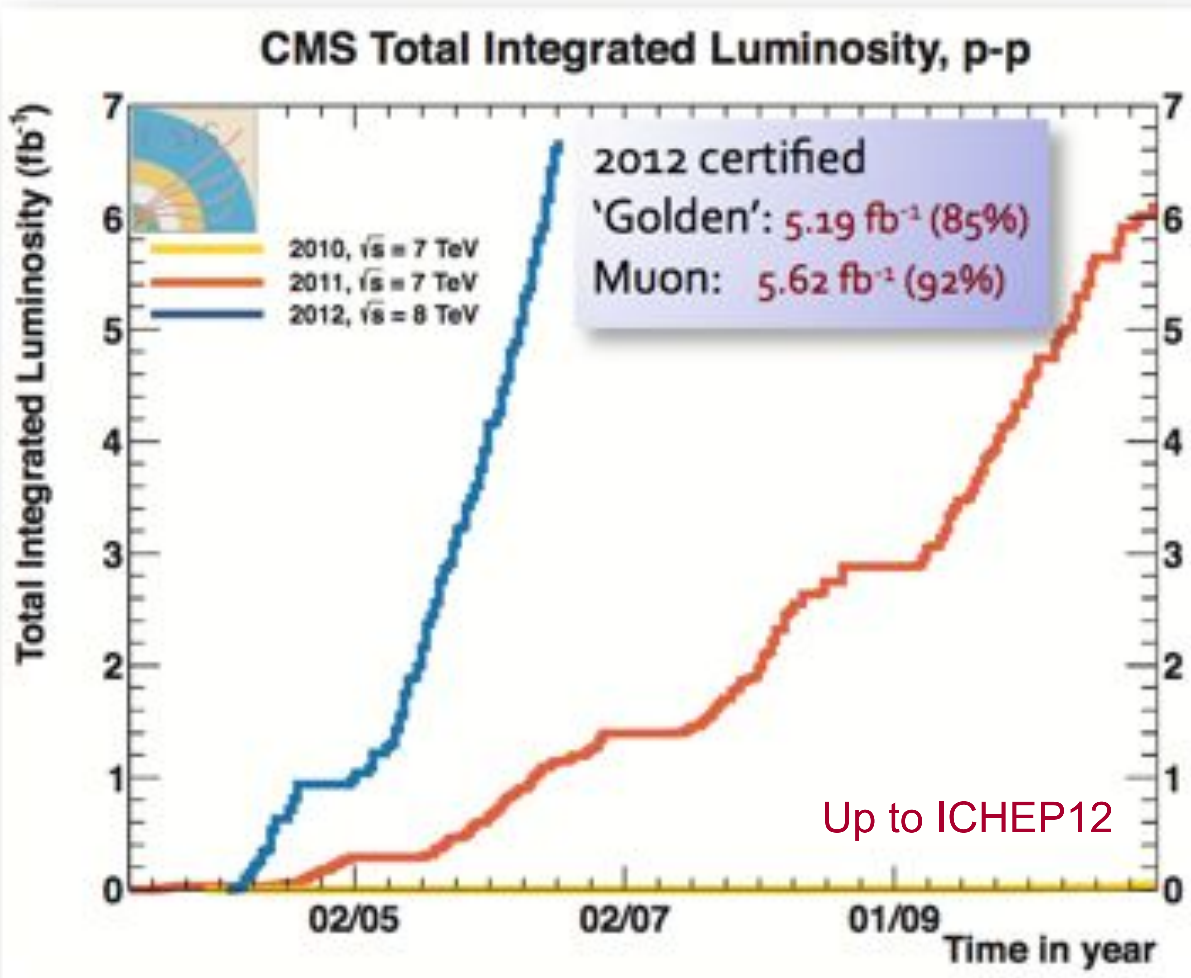
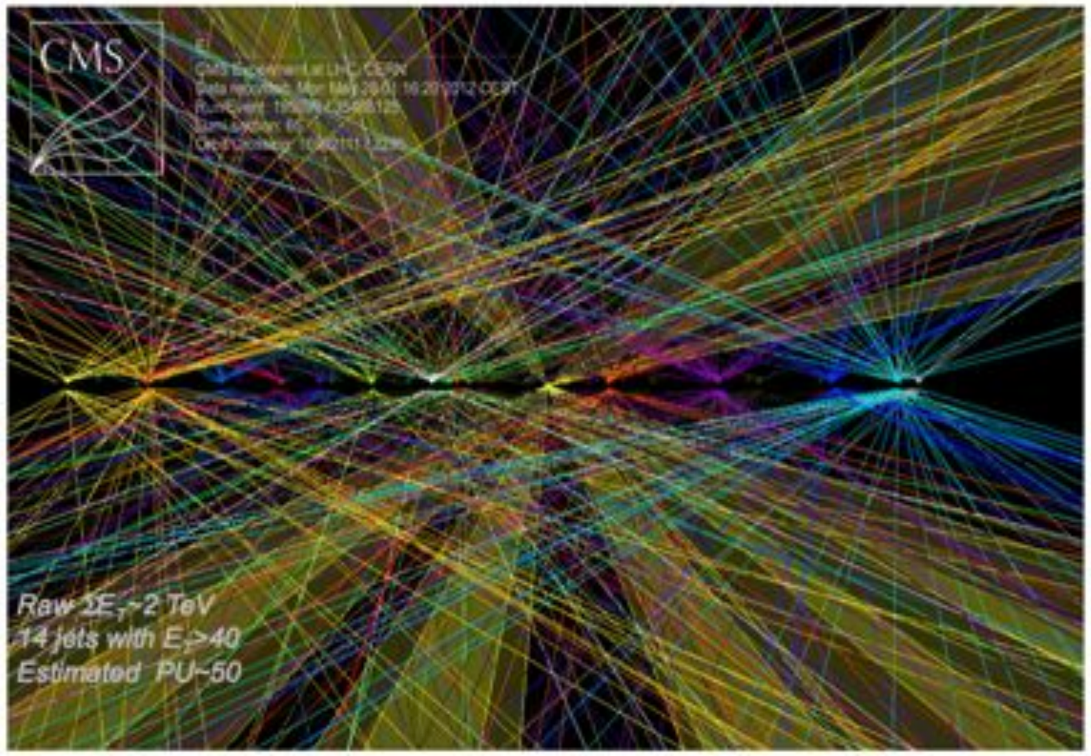
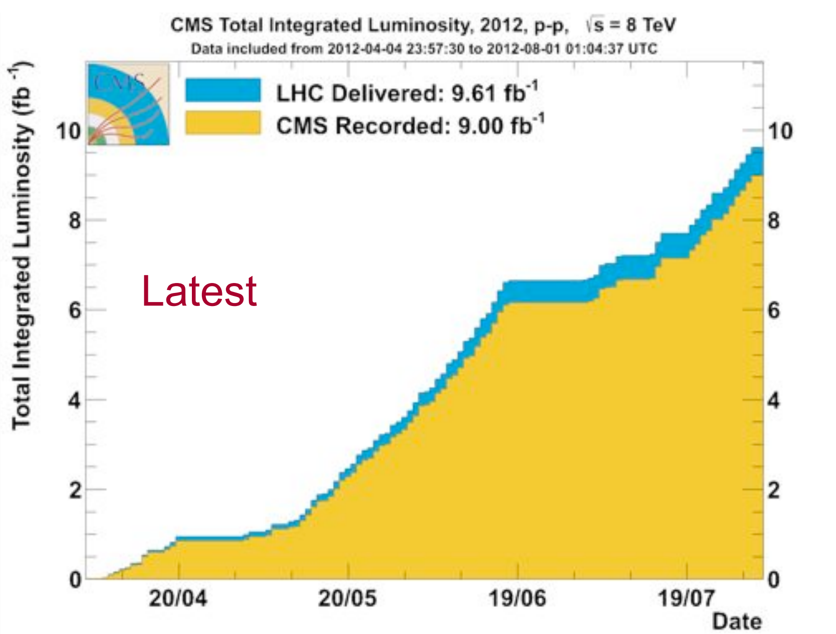


High lumi comes at a cost: in 2012 already exceeding detectors design capabilities for pile-up



2012: on average O(20) pile-up events
50 ns inter-bunch spacing



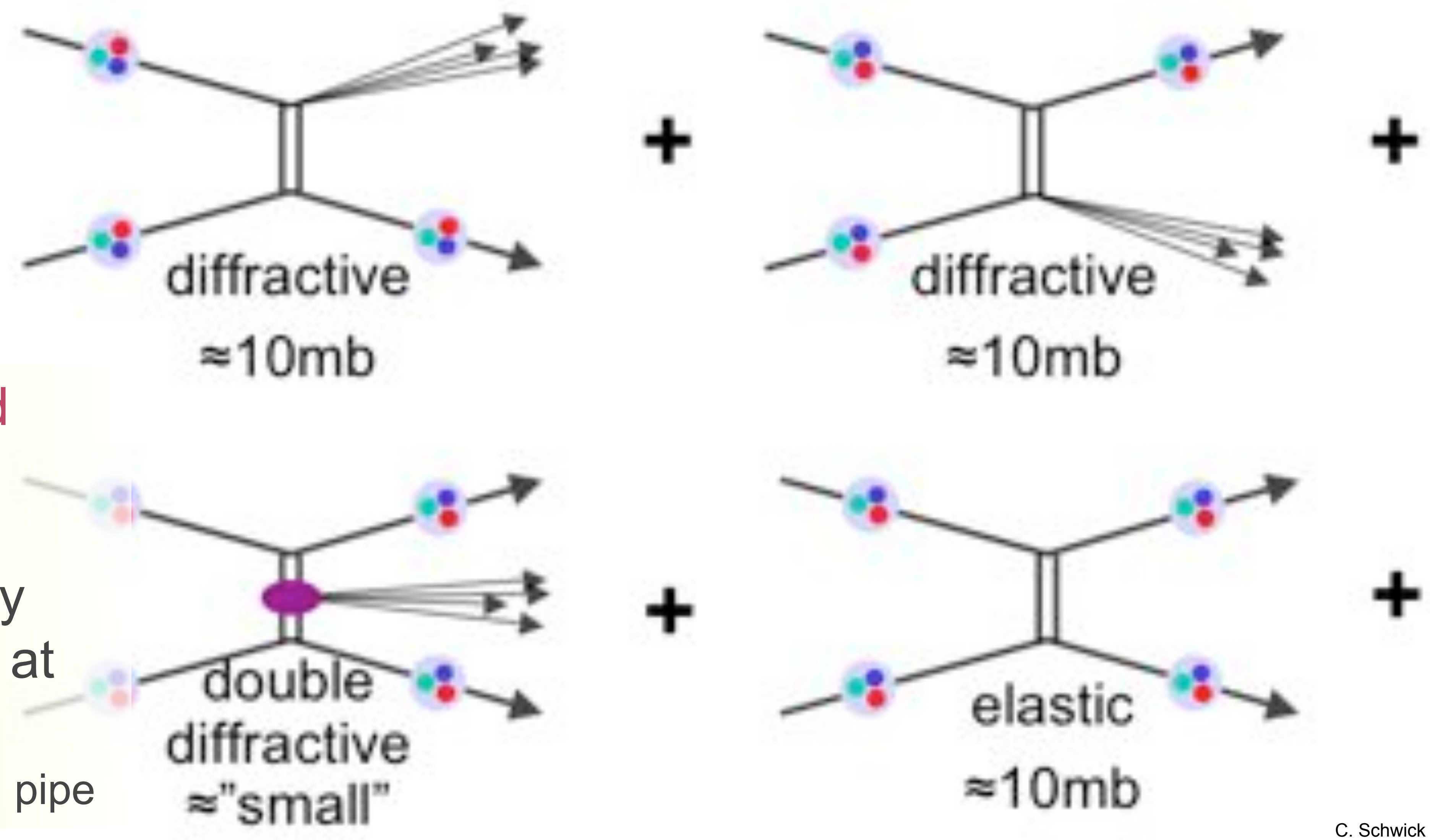
Very large Pile-Up: impact on trigger rates, computing/reconstruction time, reconstruction efficiencies (eg. isolation), jet energy reconstruction, ...

Again, Pflow helps...

pp-Interactions at the LHC

$\sigma_{tot} =$

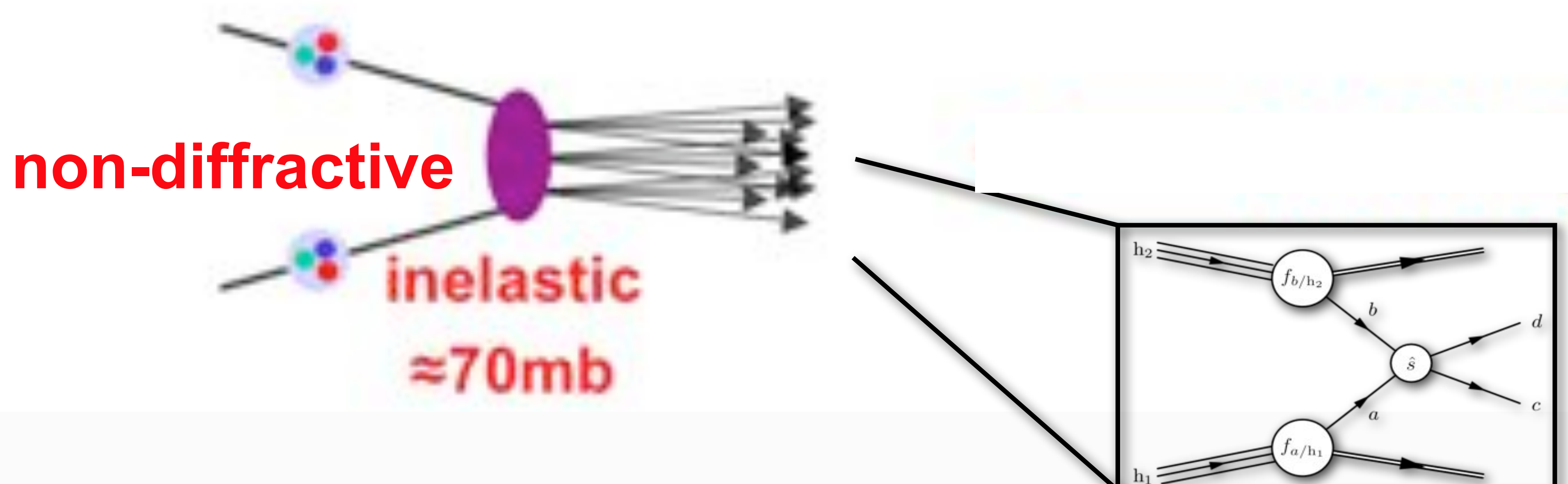
≈100mb



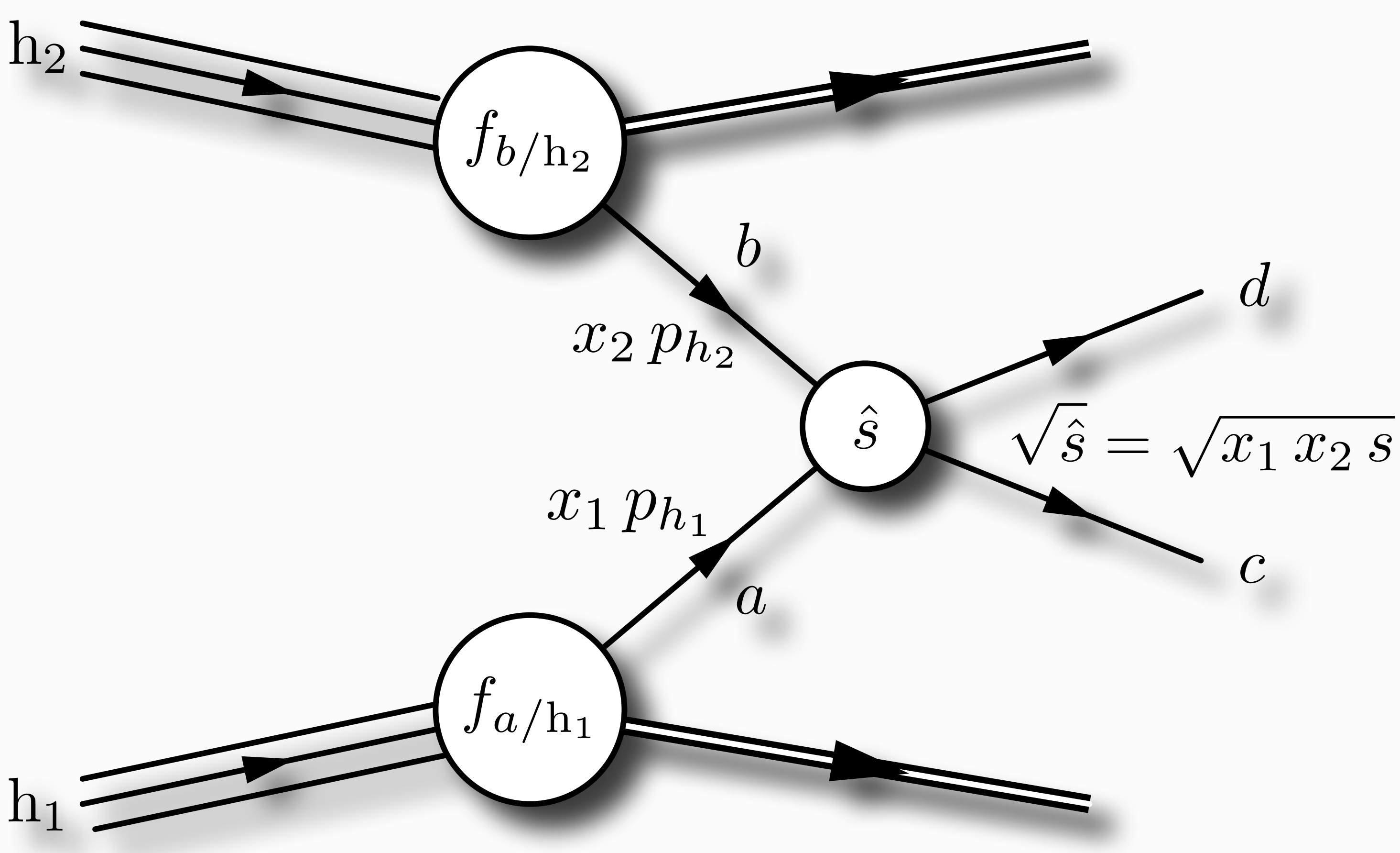
For diffractive and elastic scattering:

Put dedicated very forward detectors at small angles,
ie. very close to beam pipe

C. Schwick



The hard scattering



To produce (at central rapidity, ie. $x_1 \sim x_2$) a mass of

	LHC (7 TeV)	TEVATRON
100 GeV	x~0.014	0.05
3 TeV	x~0.43	--

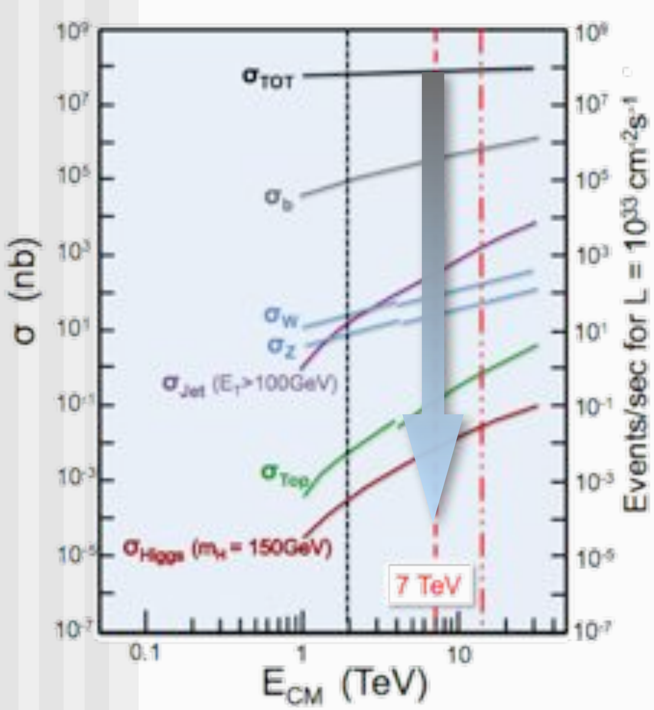
$$d\sigma(h_1 h_2 \to cd) = \int_0^1 dx_1 dx_2 \sum_{a,b} f_{a/h_1}(x_1, \mu_F^2) f_{b/h_2}(x_2, \mu_F^2) d\hat{\sigma}^{(ab \to cd)}(Q^2, \mu_F^2)$$

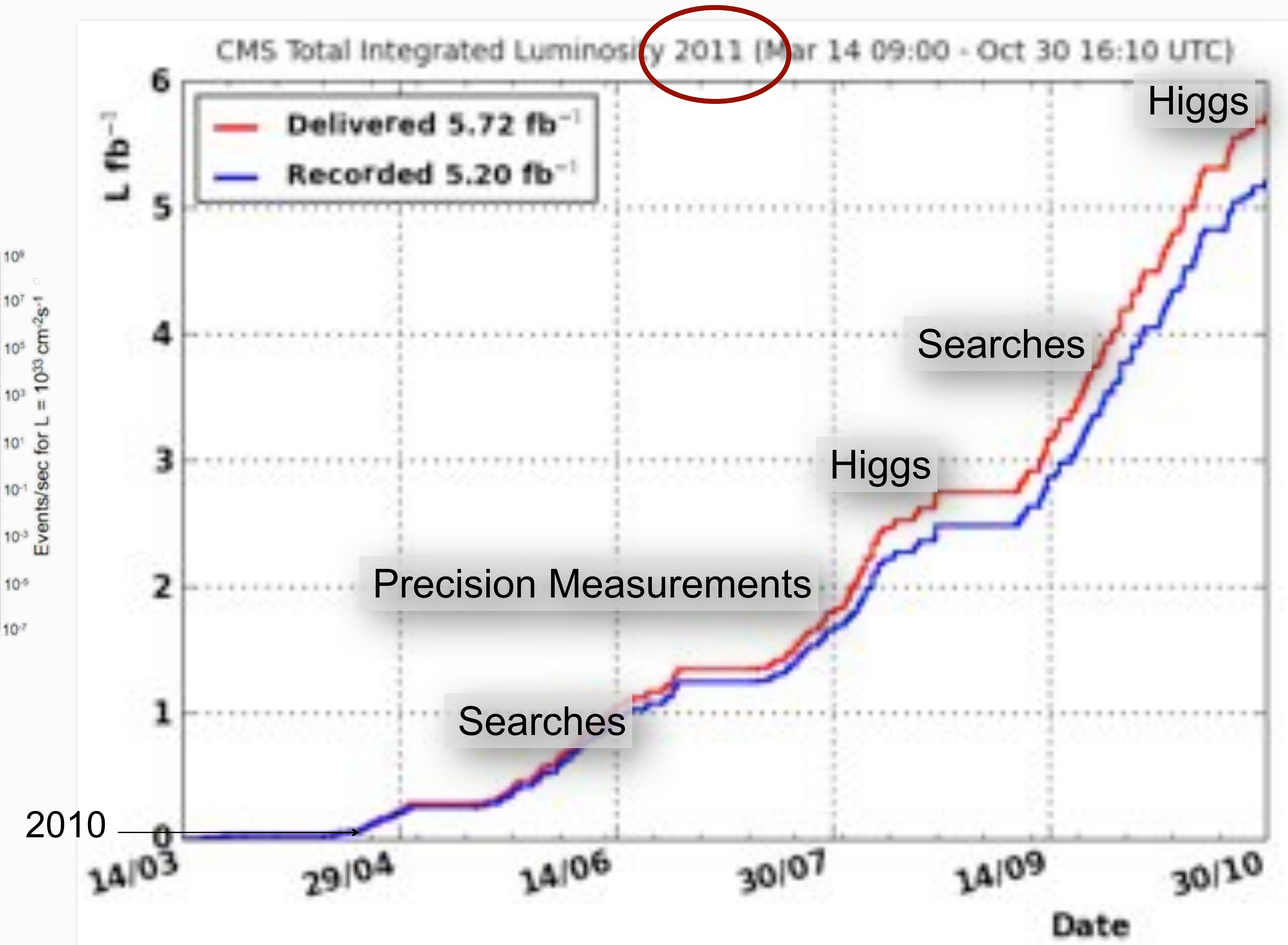
Hard Scattering = processes with large momentum transfer (Q^2)

Represent only a tiny fraction of the total inelastic pp cross section (~ 70 mb)

eg. $\sigma(pp \to W+X) \sim 150$ nb $\sim 2 \cdot 10^{-6}\, \sigma_{tot}(pp)$

As things appeared with time....





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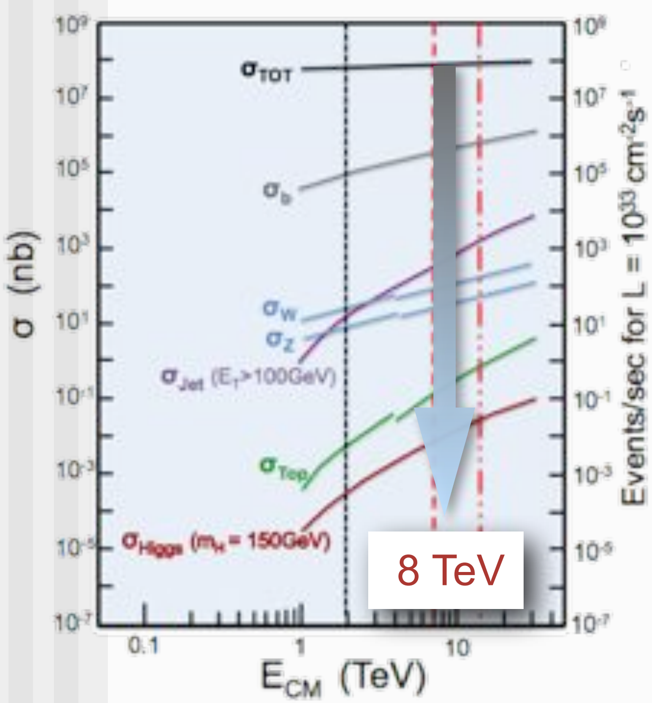
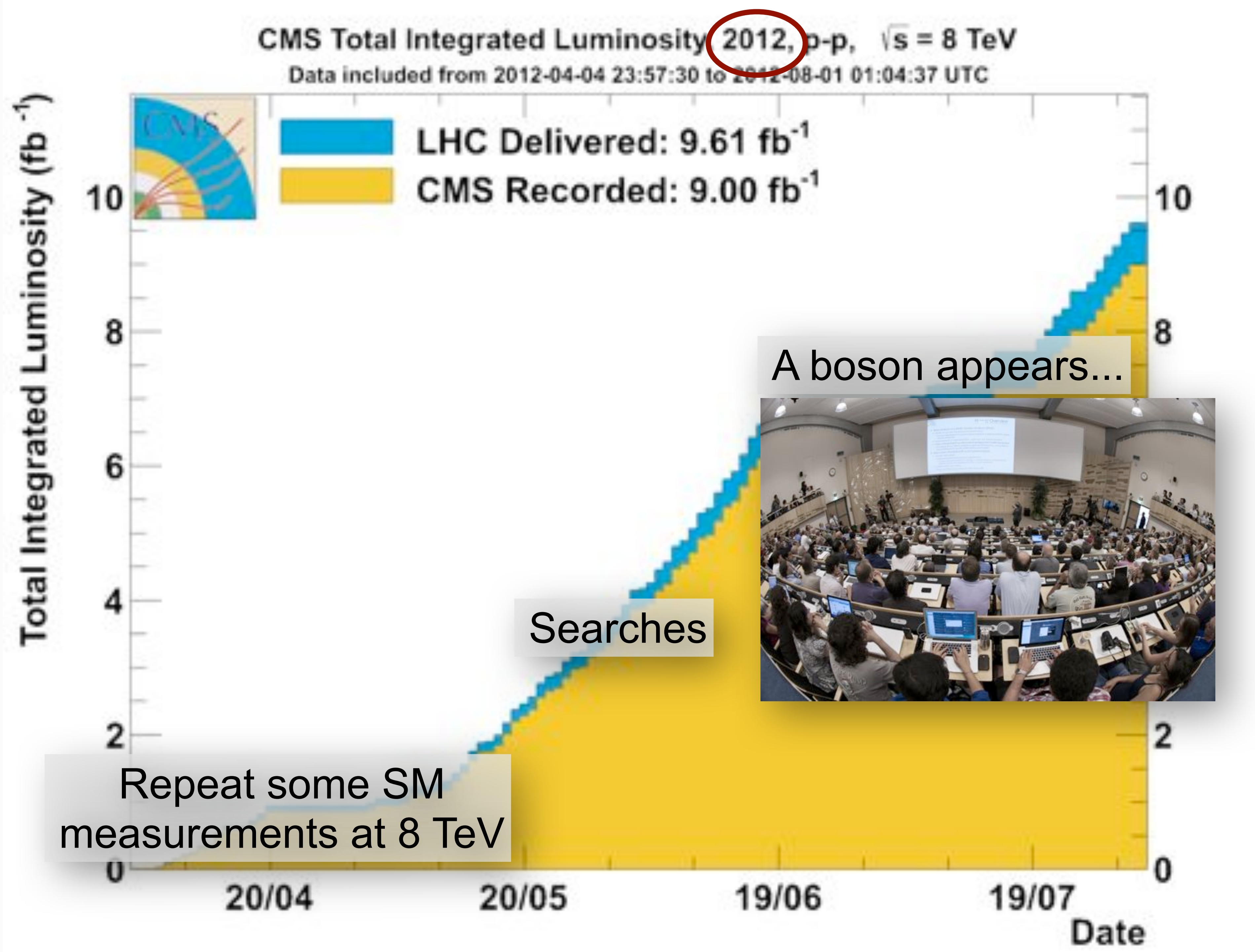




Repeat some SM measurements at 8 TeV

Searches

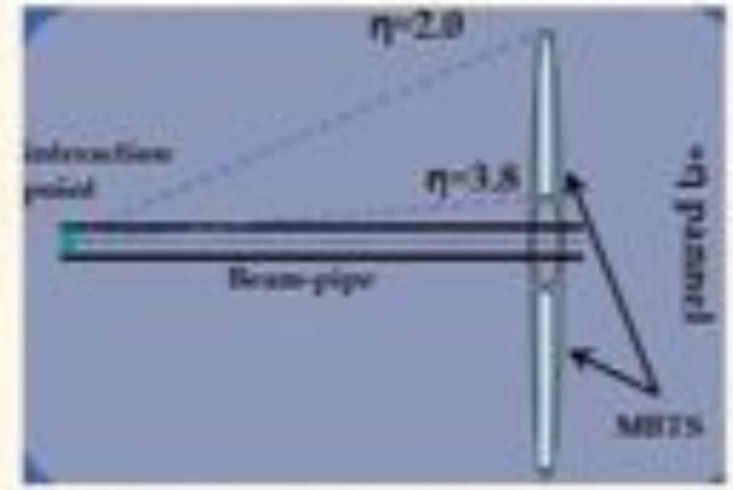
A boson appears...

Measurements of "soft" processes (low p_T)

- Understand particle production in minimum-bias pp collisions
- Test and improve phenomenological models of non-pert. QCD effects
- Tune parameters of model implementations in Monte Carlo generators
- Understand the underlying event, tune parameters

Minimum Bias Events

- Minimum bias is an experimental definition, defined by experimental trigger selection and analysis



- Relation to Physics:

$$\sigma_{measured} = f_{sd}\,\sigma_{sd} + f_{dd}\,\sigma_{dd} + f_{nd\text{-}inelestic}\,\sigma_{nd\text{-}inelastic}$$

where f_i are the efficiencies for different physics processes determined by the trigger

NB: need to understand what is measured
to allow comparison to previous results,
often presented for non-single diffractive events

K. Jakobs CHIPP PhD Winter School, Ascona, Jan. 2010

First results at LHC ....

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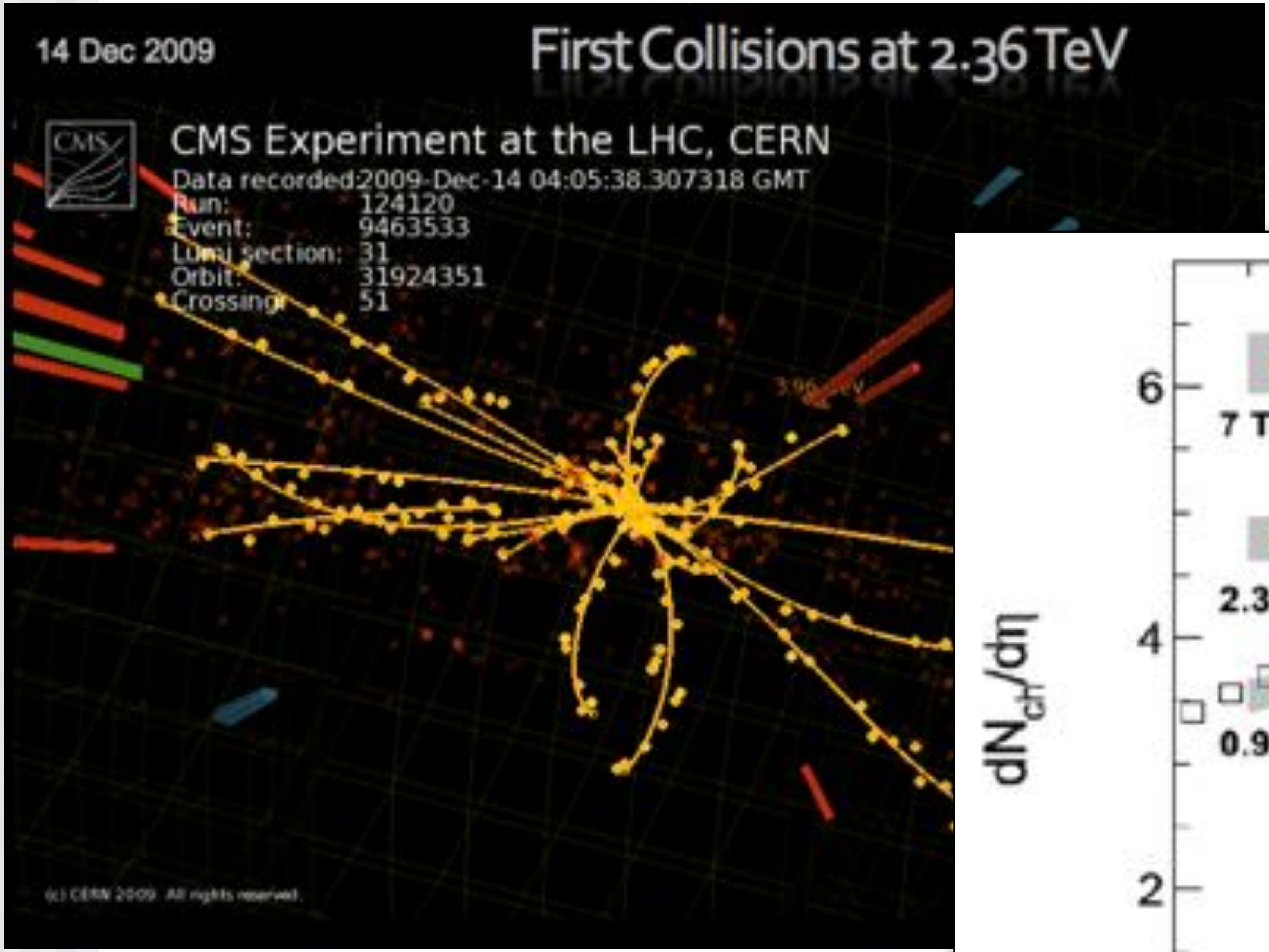
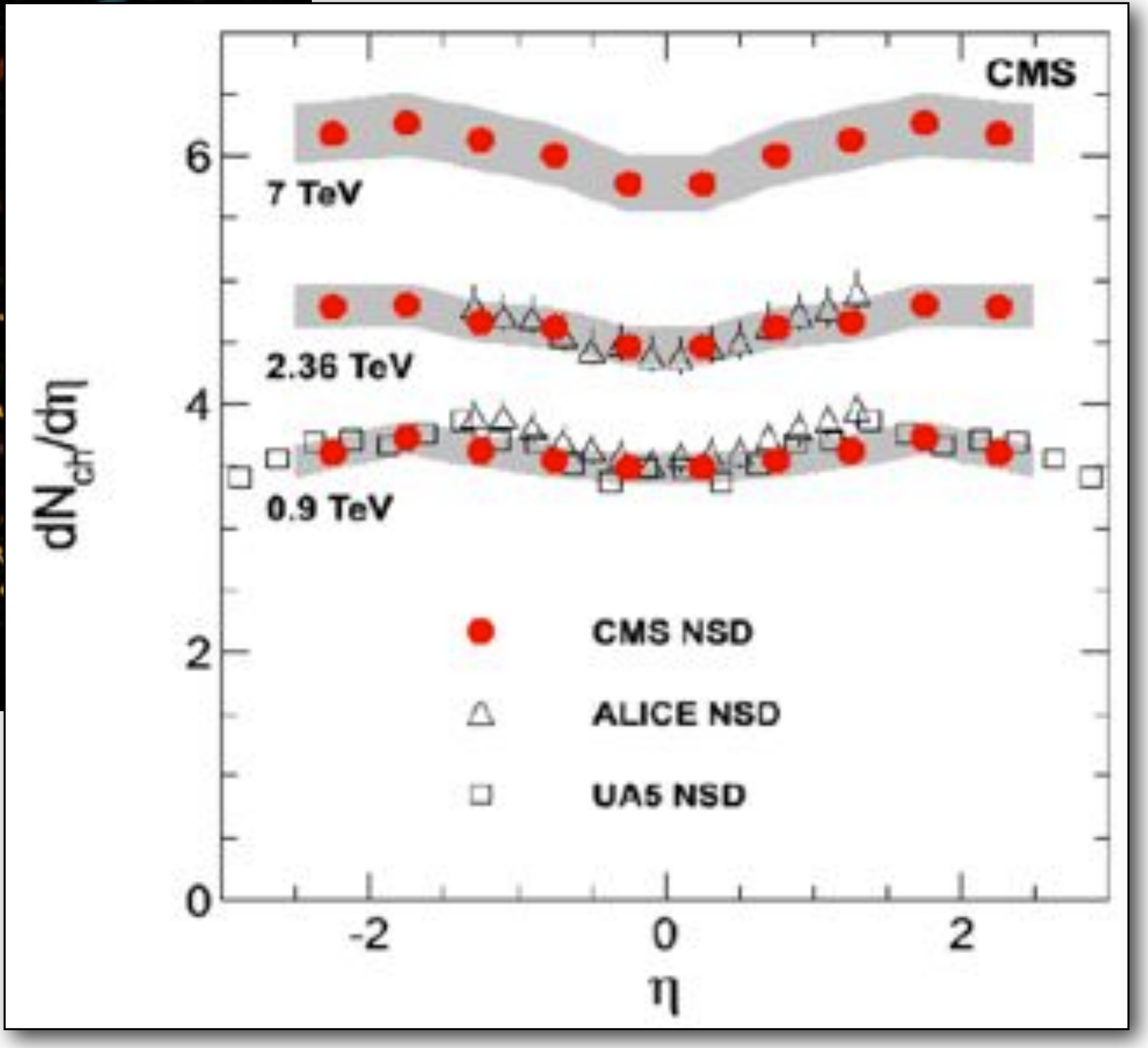


- first publications by LHC experiments !



- ❑ dN/dη at 0.9, 2.36 and 7 TeV
  - correction for NSD (~6% corr. →2.5% syst)

CMS PRL 105, 022002 (2010)

Energy Dependence

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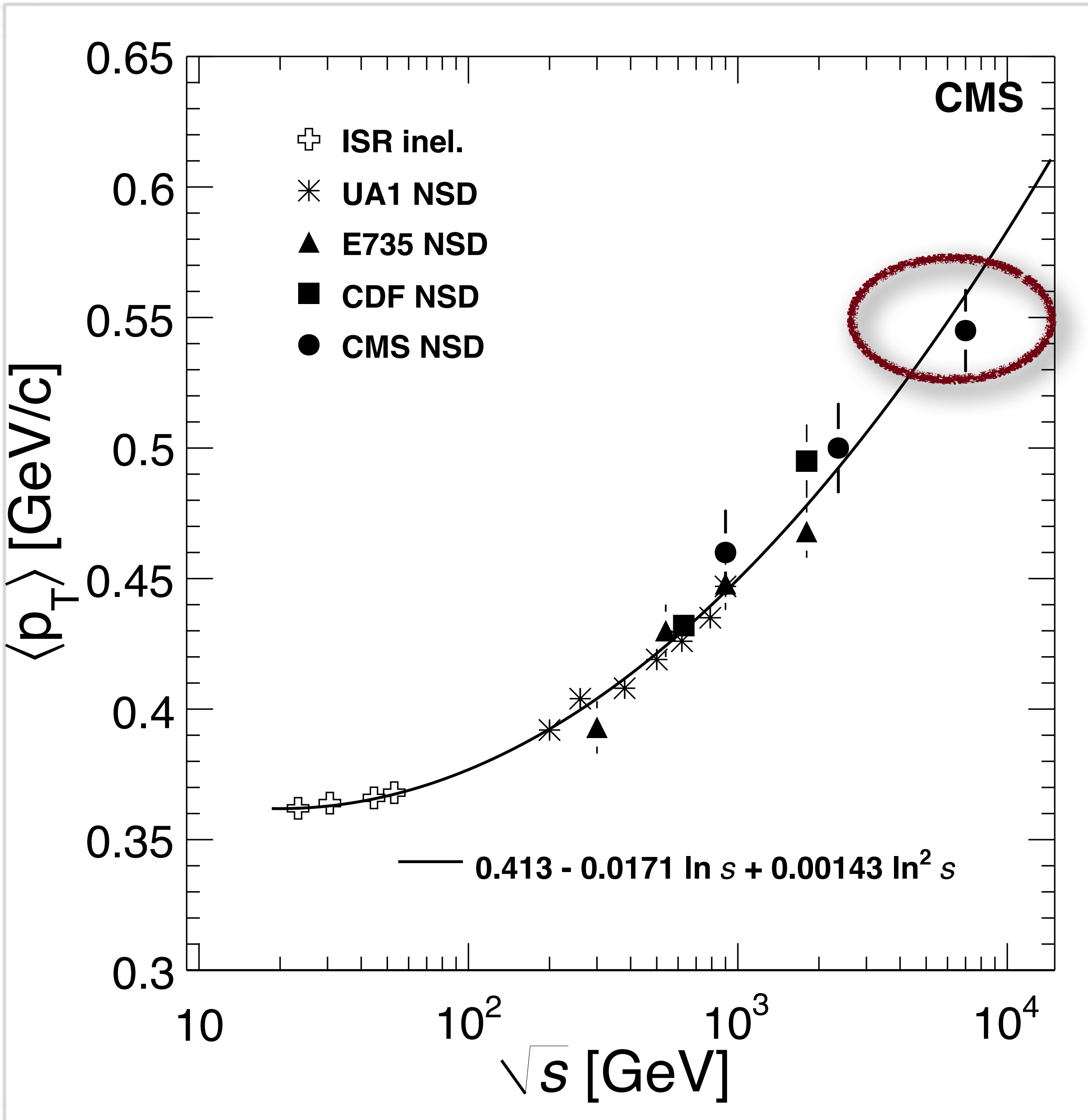
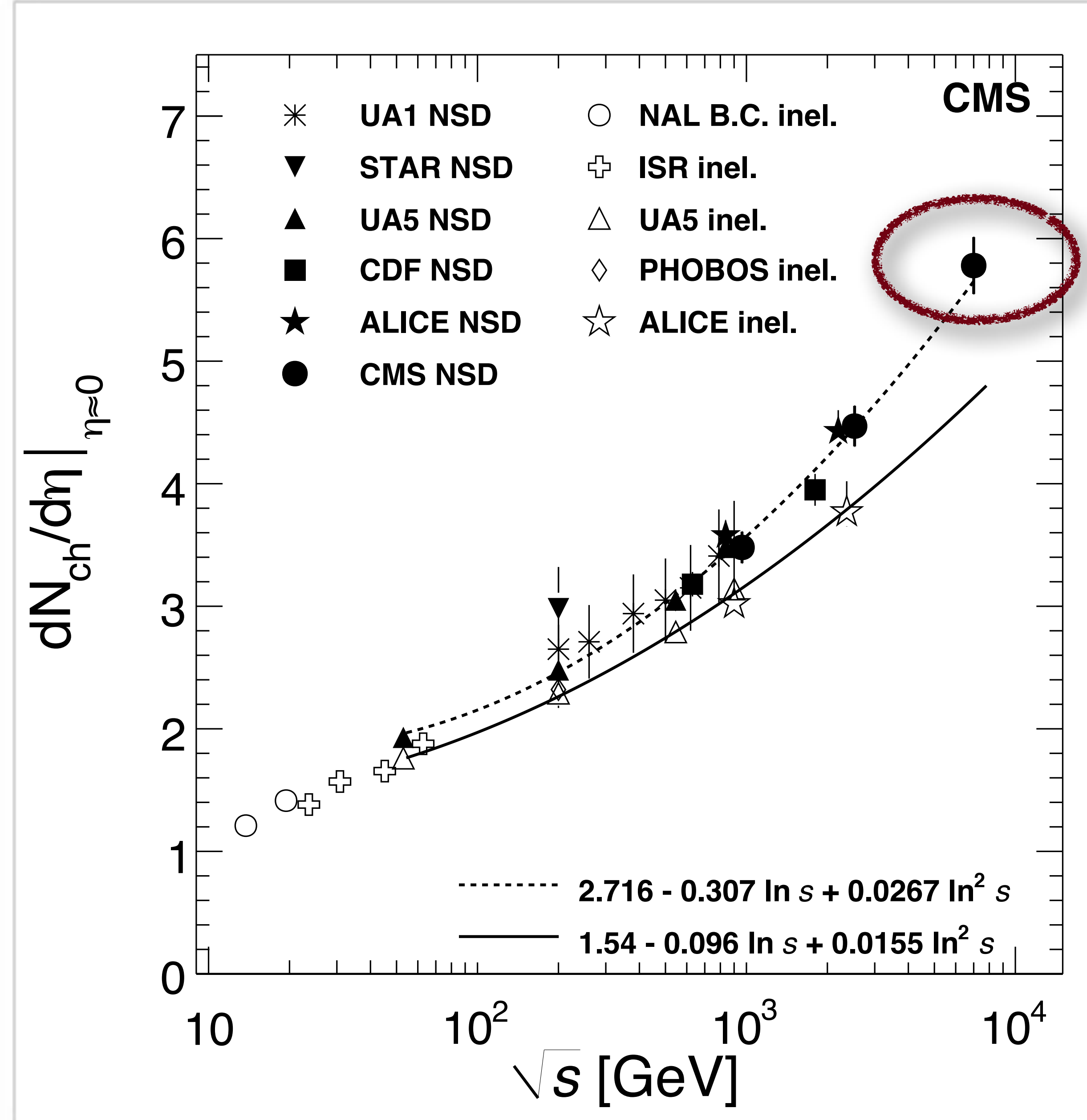
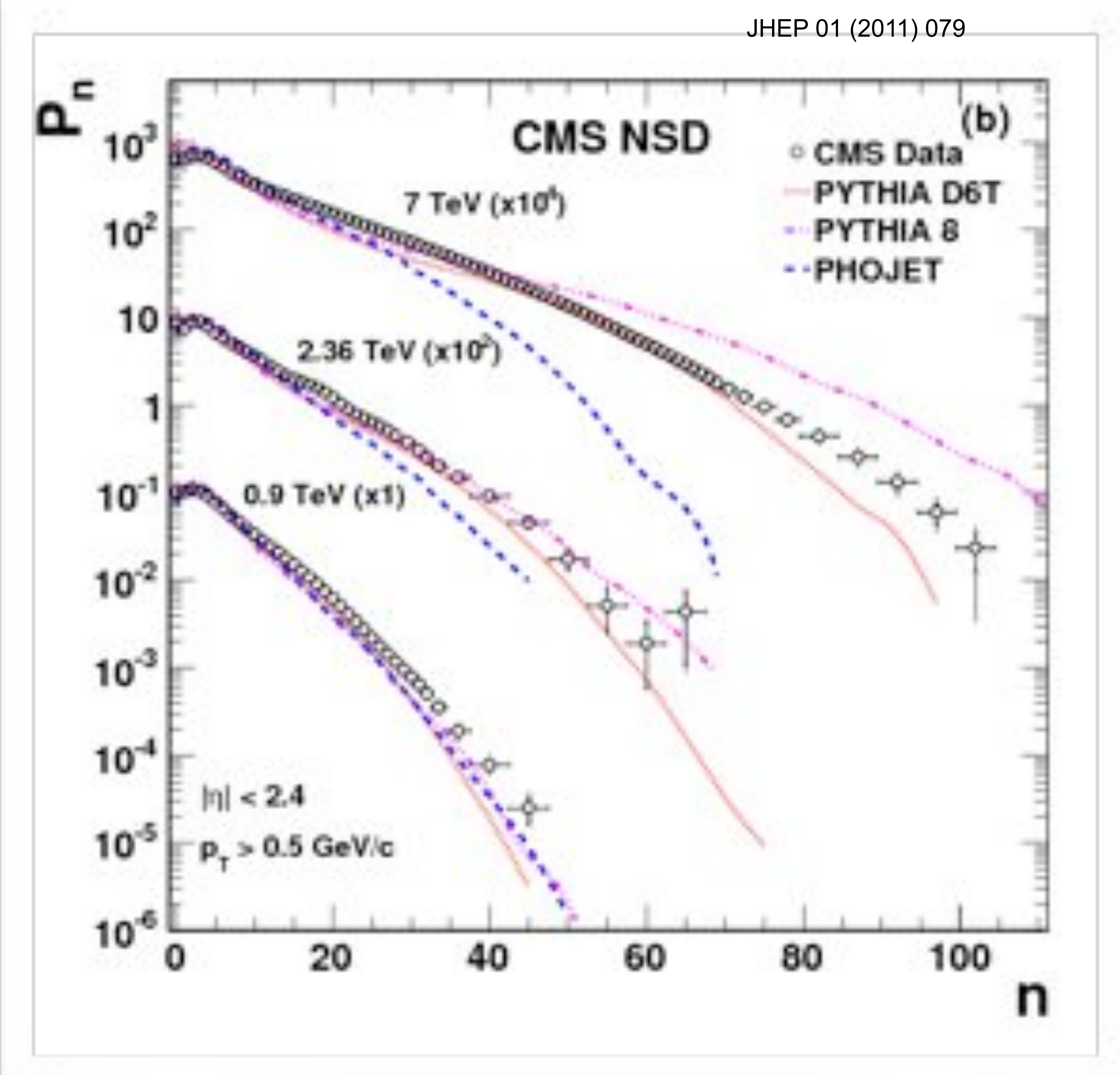
Phys. Rev. Lett. 105 (2010) 022002

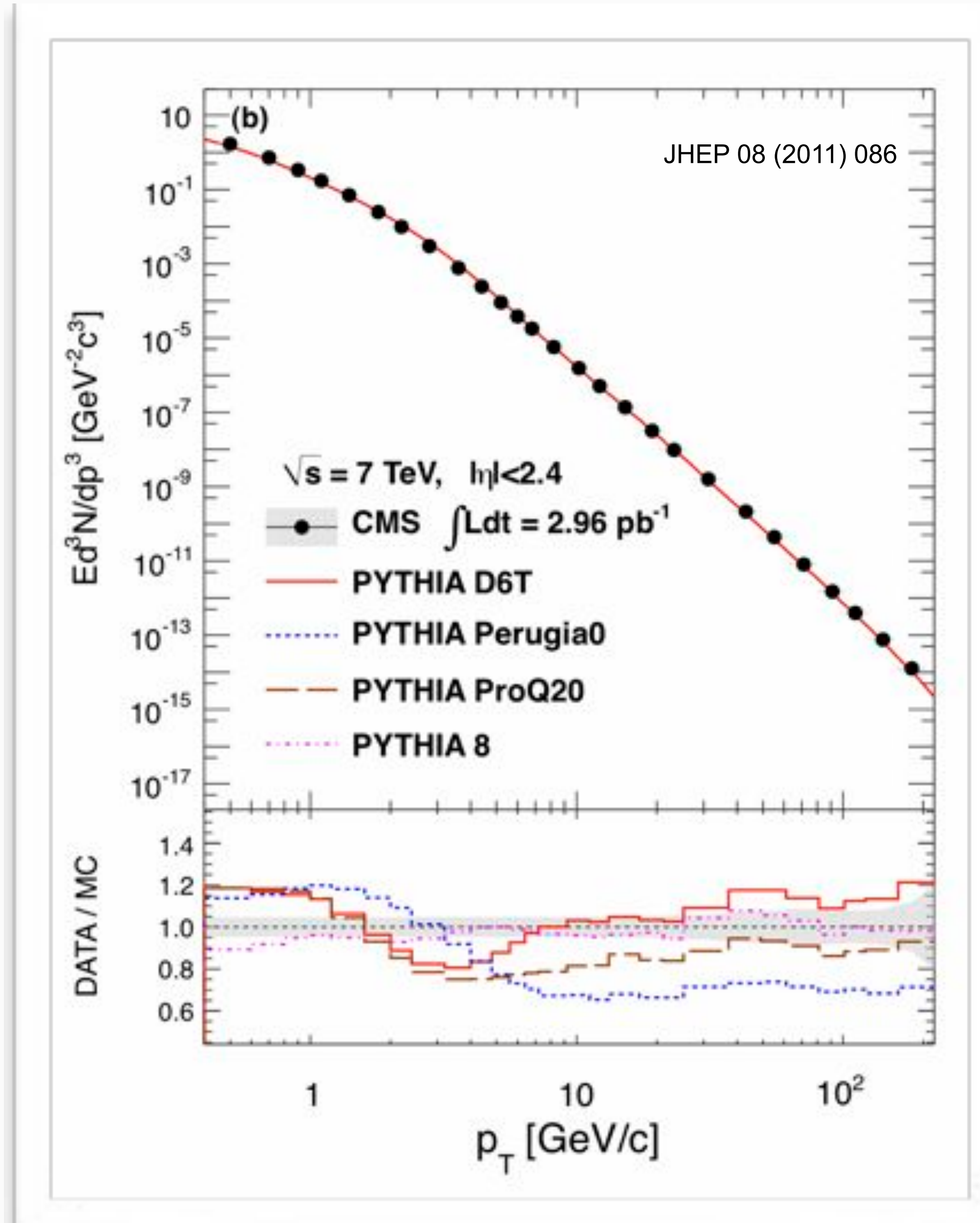




- at 7 TeV:
  - ~ 6 x 5 (rapidity coverage of tracker) = 30 chg. particles in tracker acceptance
  - with on average 500-600 MeV of trans. momentum

Chg. particle mult. and p_T distributions





- showed need to improve (tuning of) models
- turned out: in general higher mult. than expected, difficult or impossible to get excellent description of mult. and full p_T dist.
- and for simultaneously getting central and forward chg. particle production right

Underlying Event : Definition

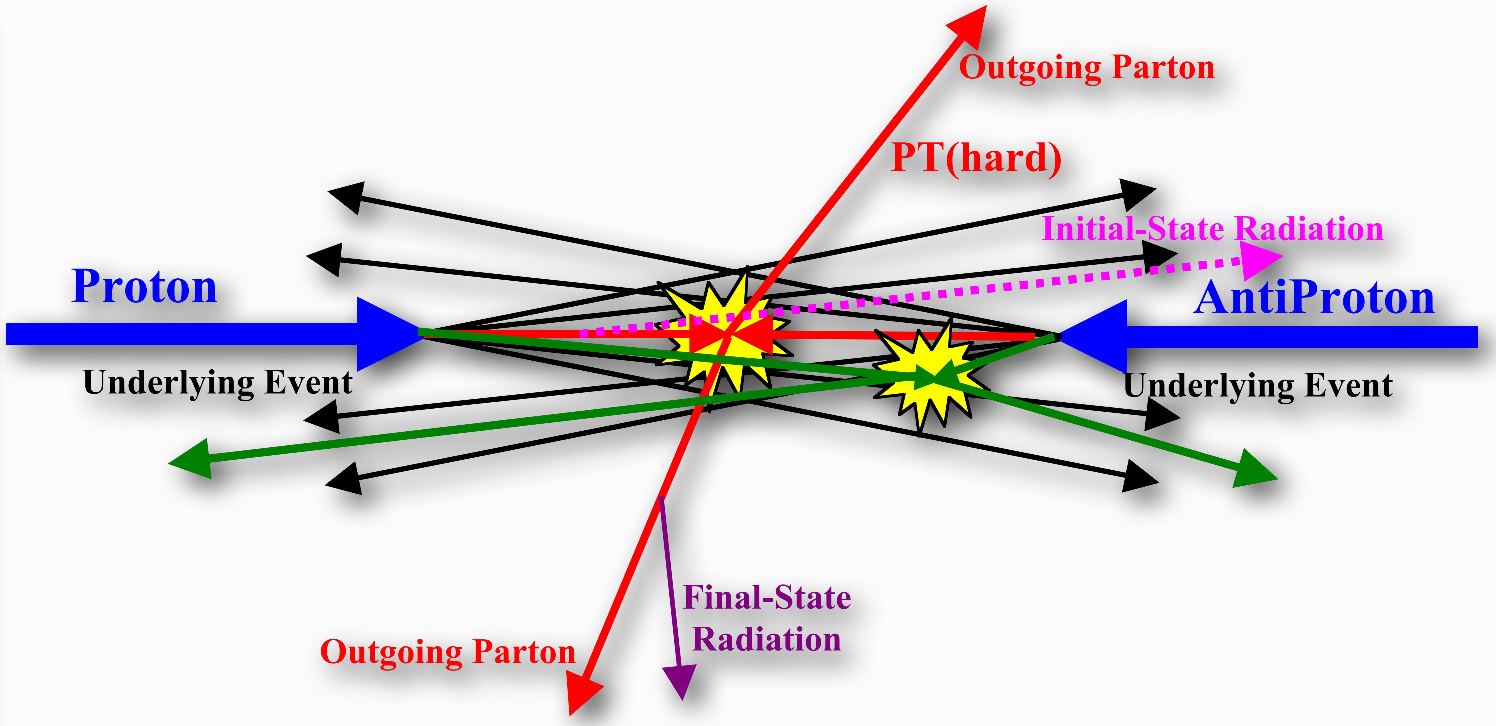
The Underlying Event:

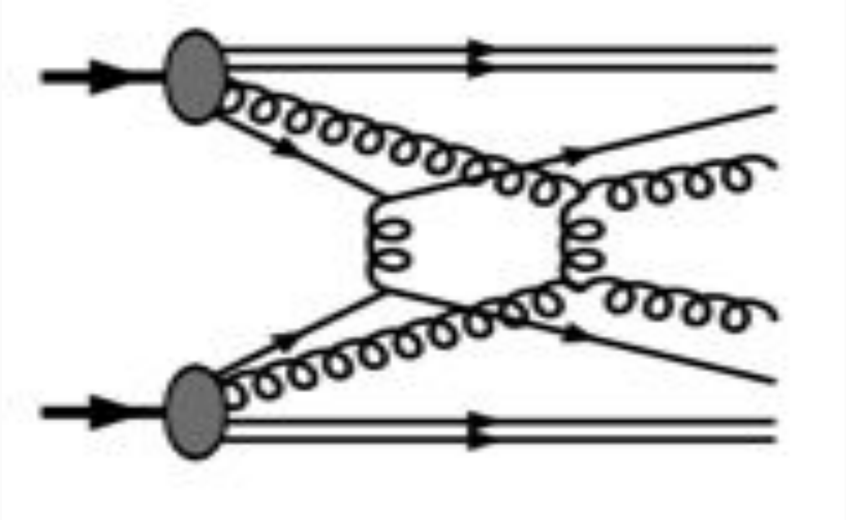
The products of
beam-beam remnant
multiple-parton interactions

i.e extra activity besides
hard scattering

which cannot uniquely be separated from

ISR, FSR



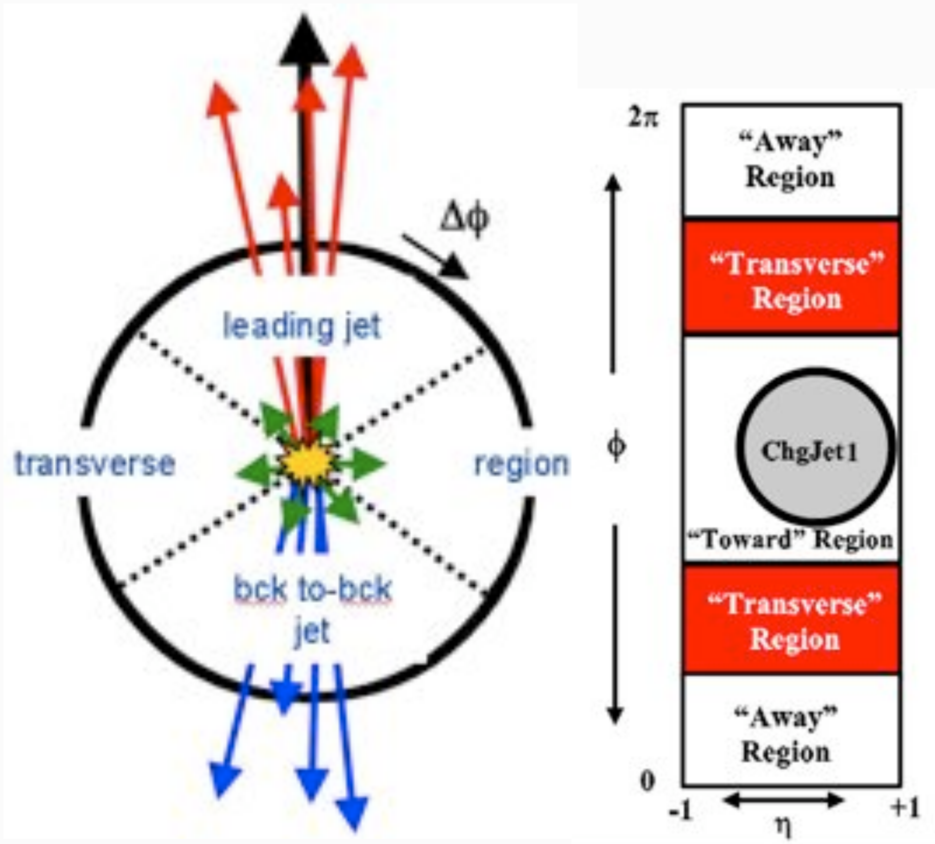


Issues / interesting questions /

Motivations:

- Note : UE != MB
- Tuning of MC models, an issue is the energy dependence
- needed to understand global observations on chg. particle production
- impact on selection efficiencies (isolation), jet energy, MET, low-p_T jets, ...

UE studies : Observables



Using Charged Jets (or leading charged track)

- Topological structure of p-p collision from charged tracks
- Jets found with massless charged tracks as input
- The leading Ch_jet1 defines a direction in the phi-plane
- The transverse region is particularly sensitive to the UE

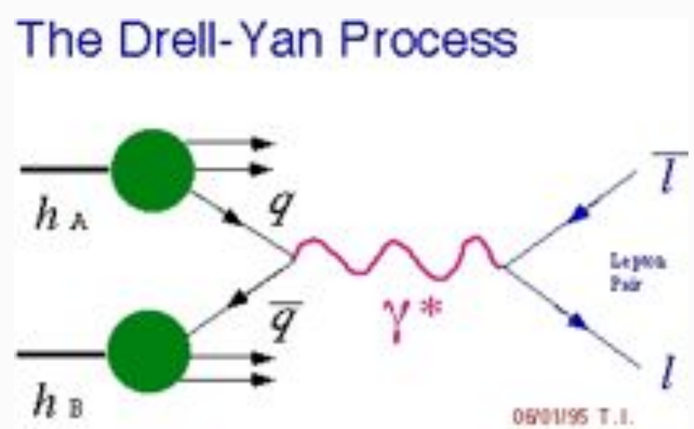
Main observables:

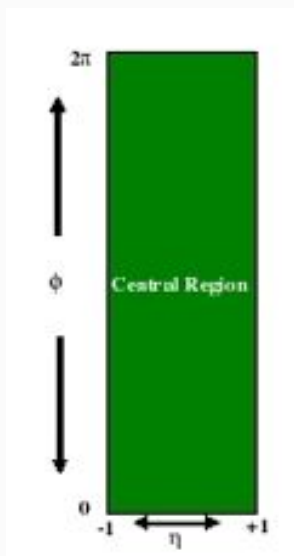
$dN/d\eta d\Phi$	charged density
$d(PT_{sum})/d\eta d\Phi$	energy density

New : jet area/median approach

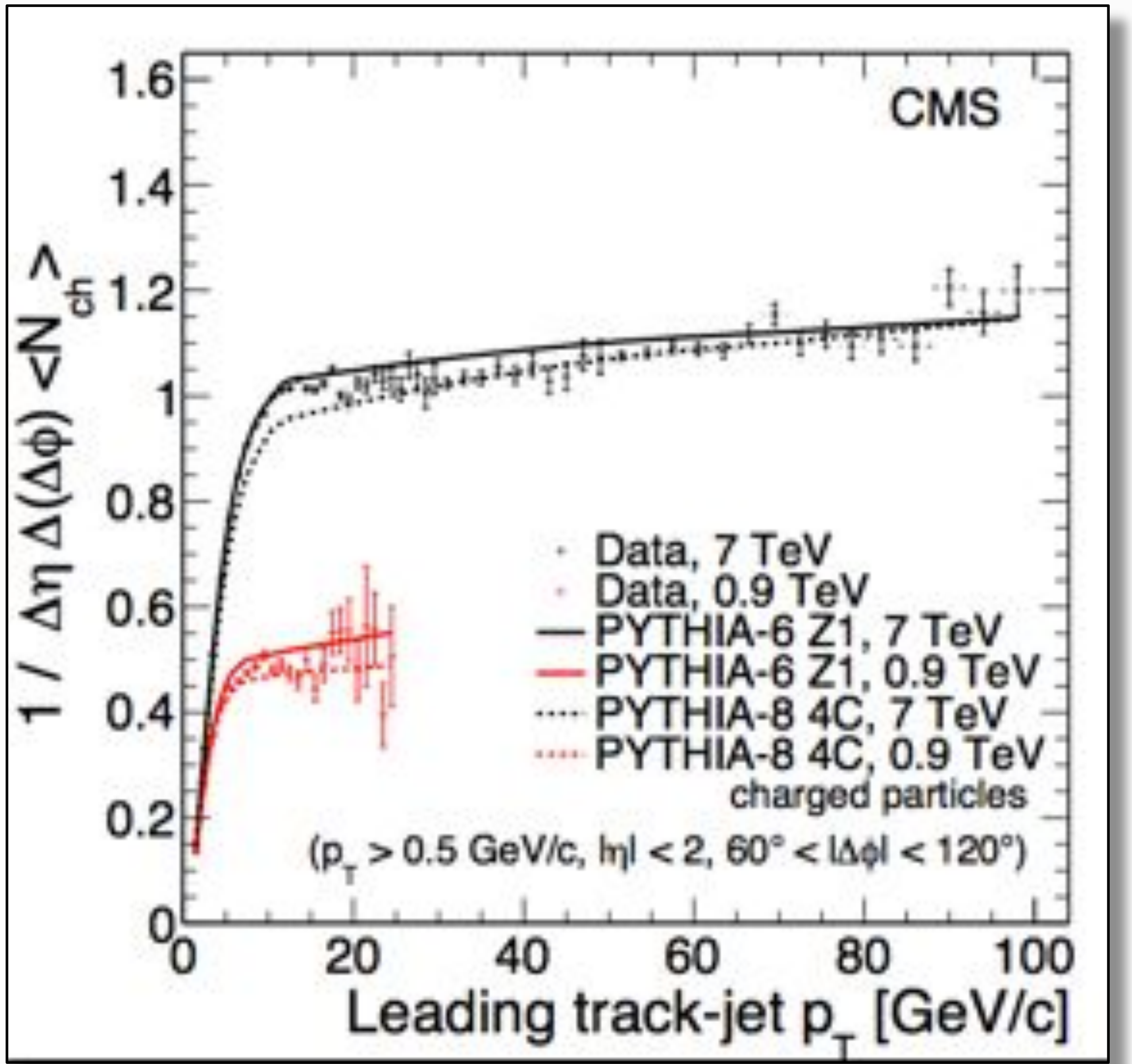
From DY muon-pair production (using muon triggers)

- defined in all the phi-plane
- after removing the muon pairs, everything else is UE

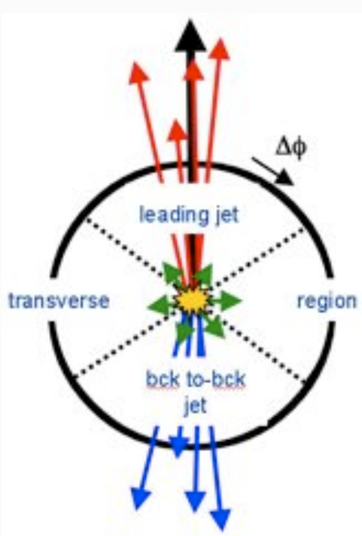




Examples of Measurements



CMS JHEP 09 (2011) 109

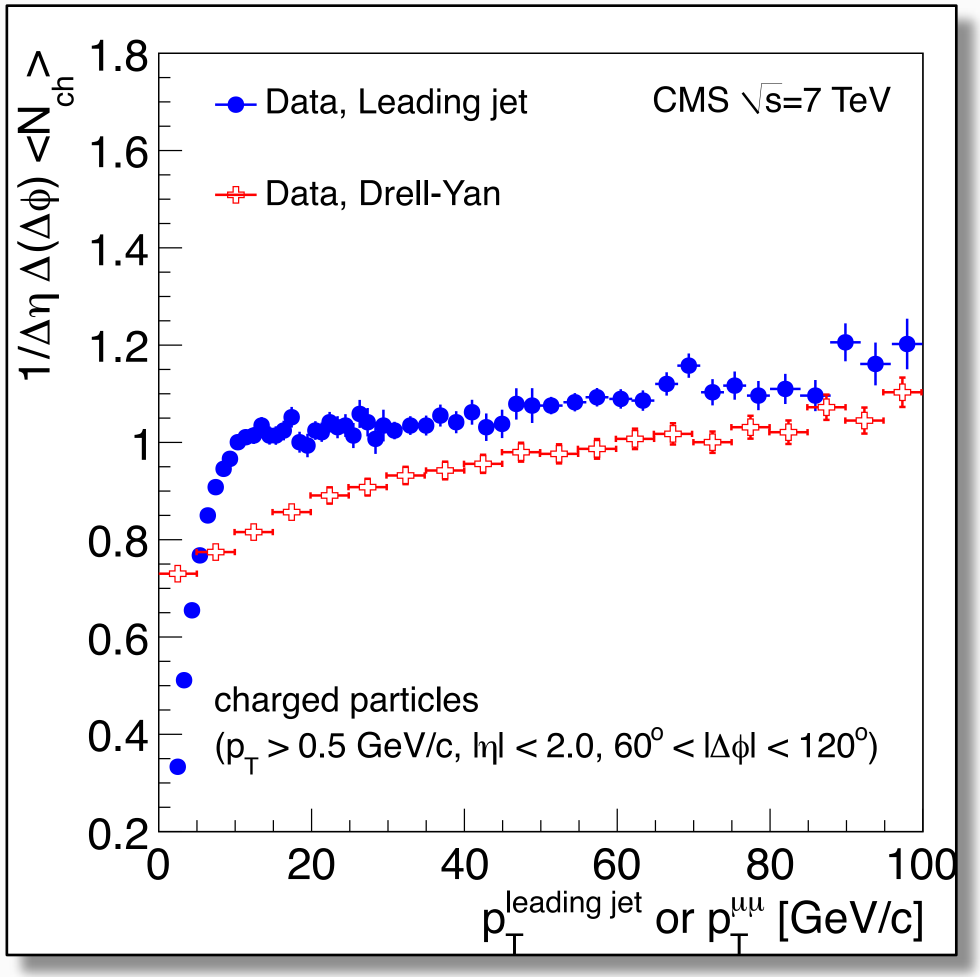


Particle Production in the transverse region

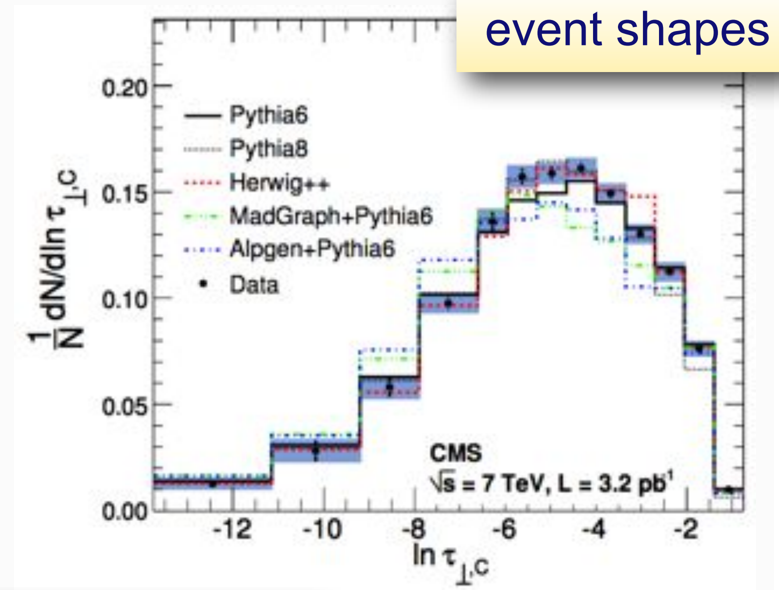
Remarks / Issues

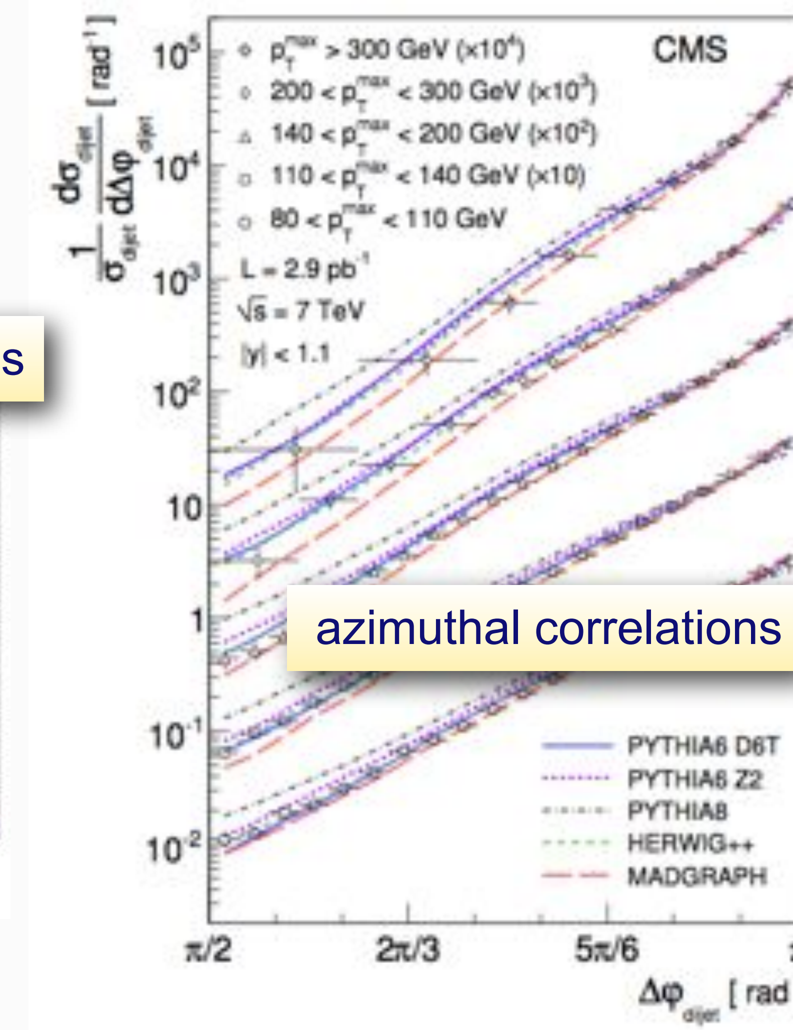
- again, found that most/all of the pre-LHC tunes failed to give good description for the whole phase space
- generally, stronger particle production in transverse region observed than expected
- special LHC tunes obtained, now used for the big MC productions

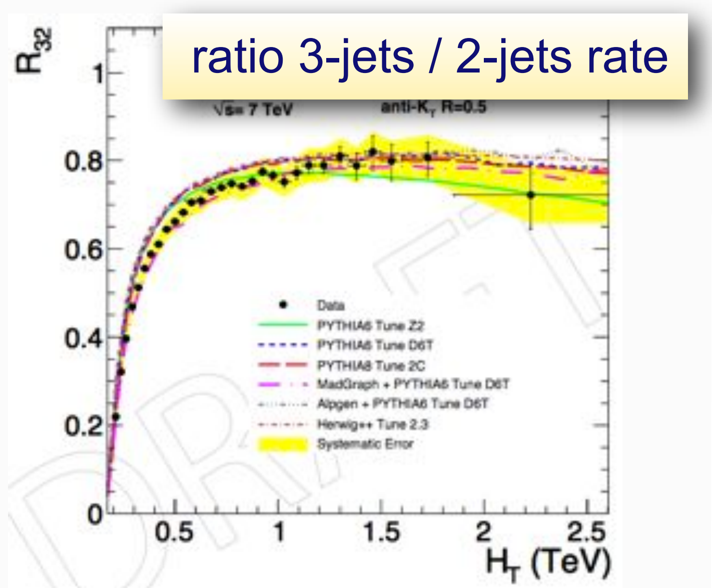
CMS PAS QCD-11-012

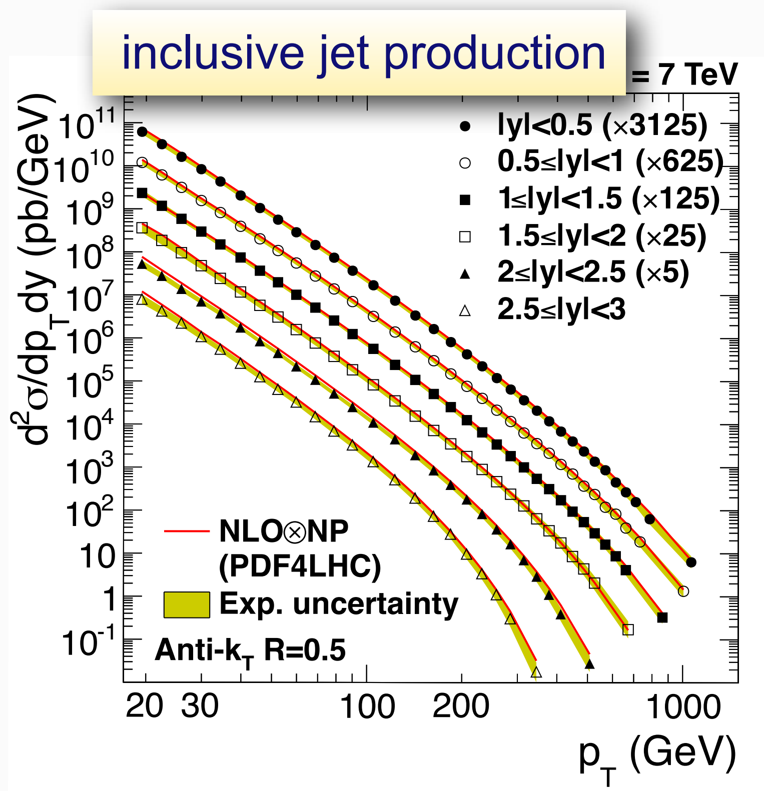


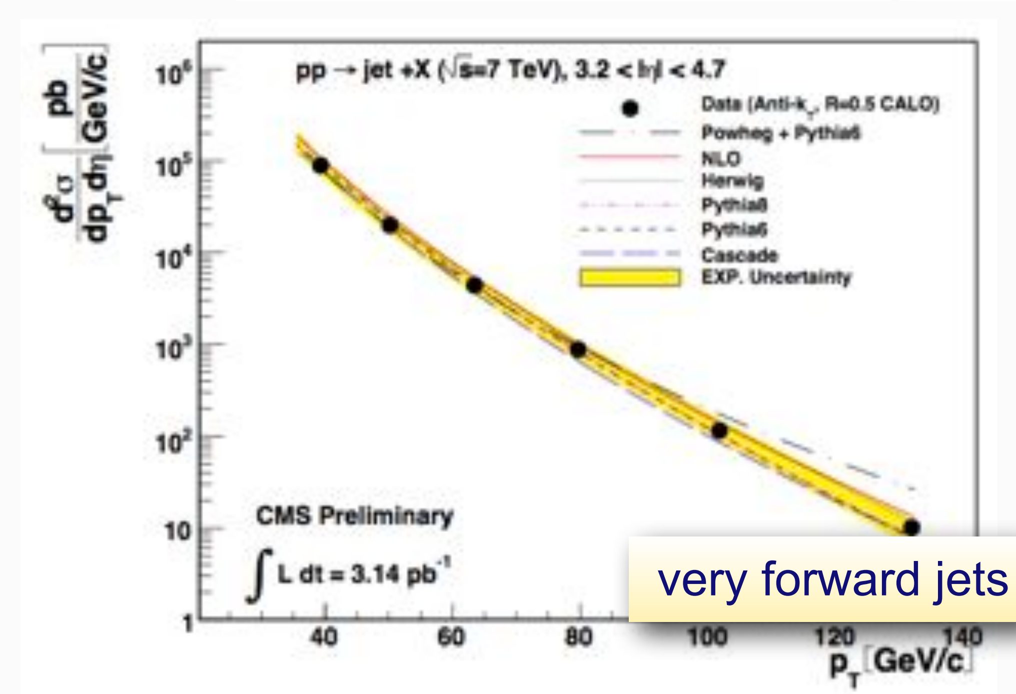
Production of Jets



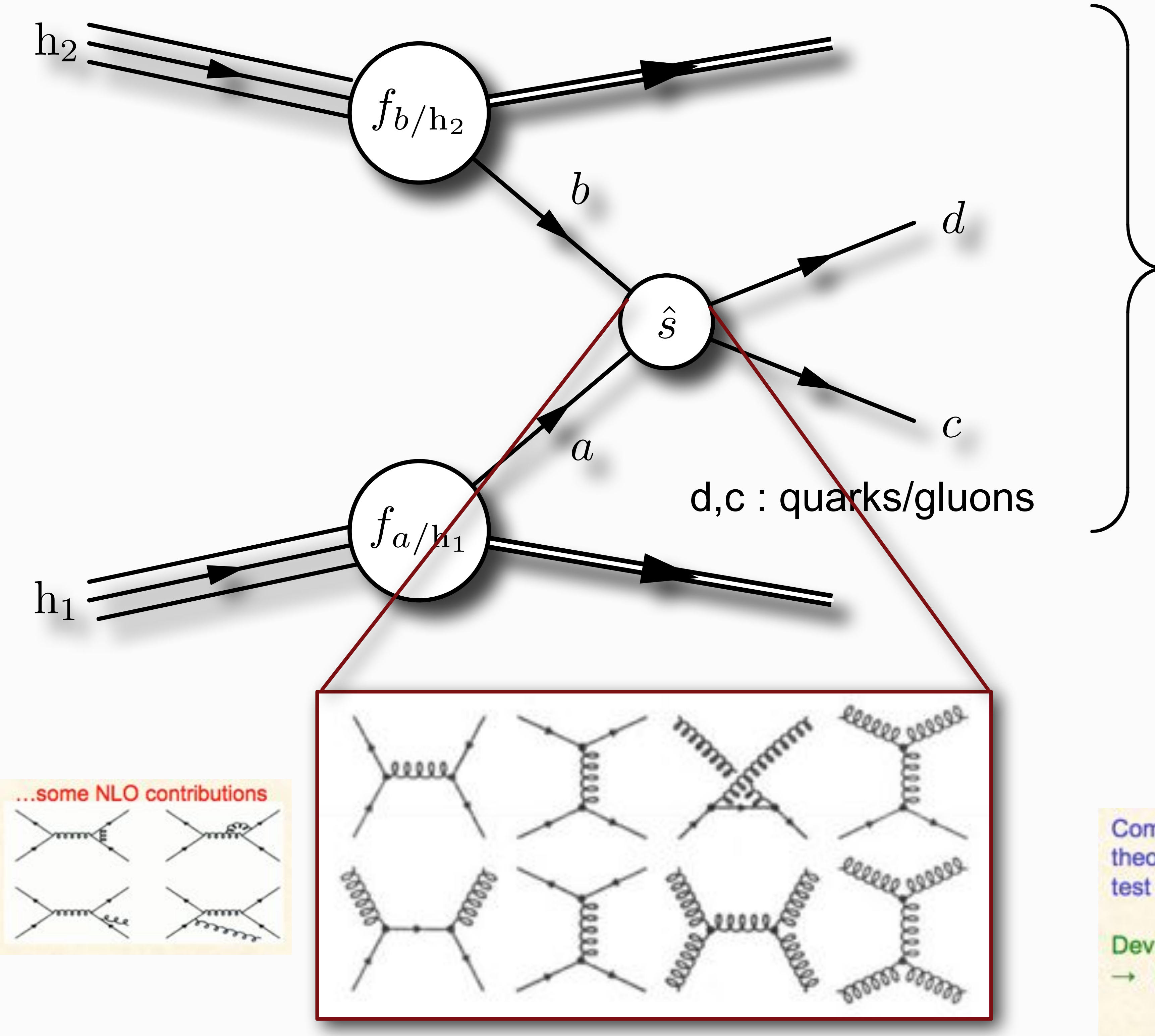


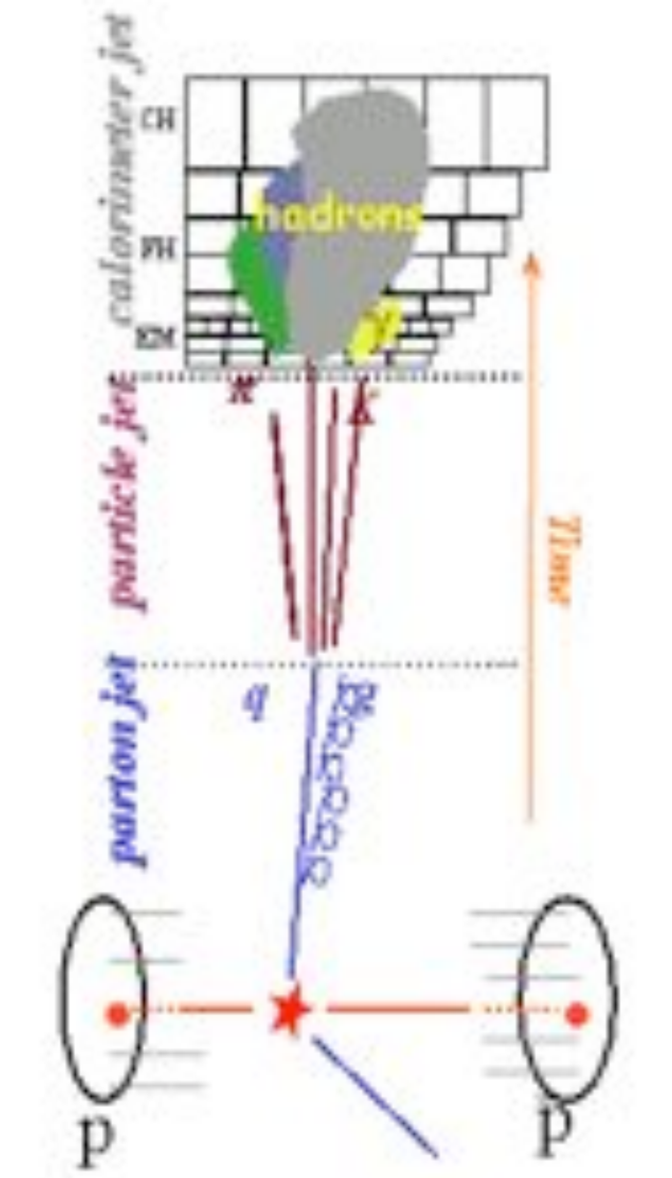






JET production at hadron colliders

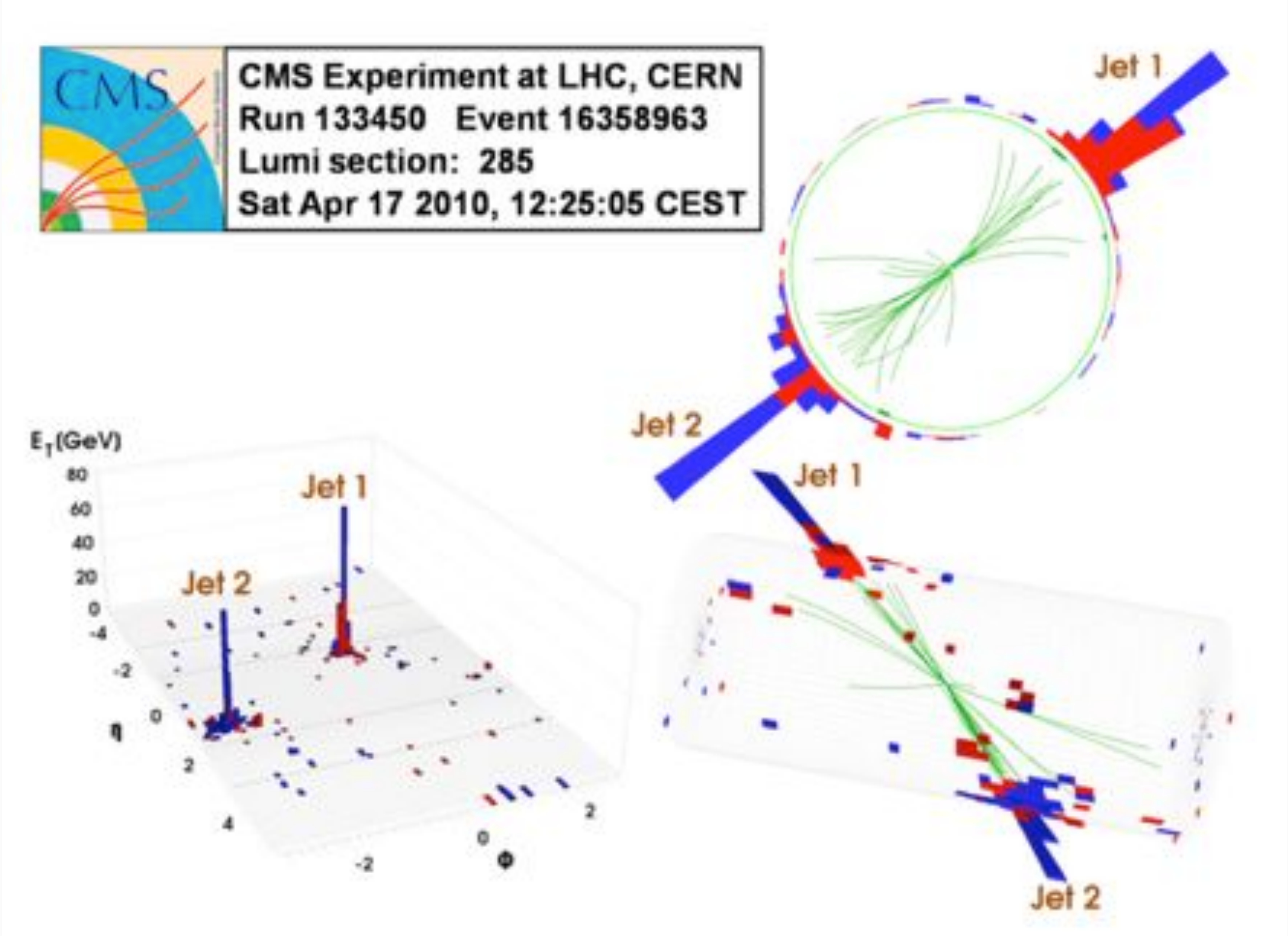




Comparison between experimental data and theoretical predictions constitutes an important test of the theory.

Deviations?
→ Problem in the experiment ?
Problem in the theory (QCD) ?
New Physics, e.g. quark substructure ?

and we really “see” jets

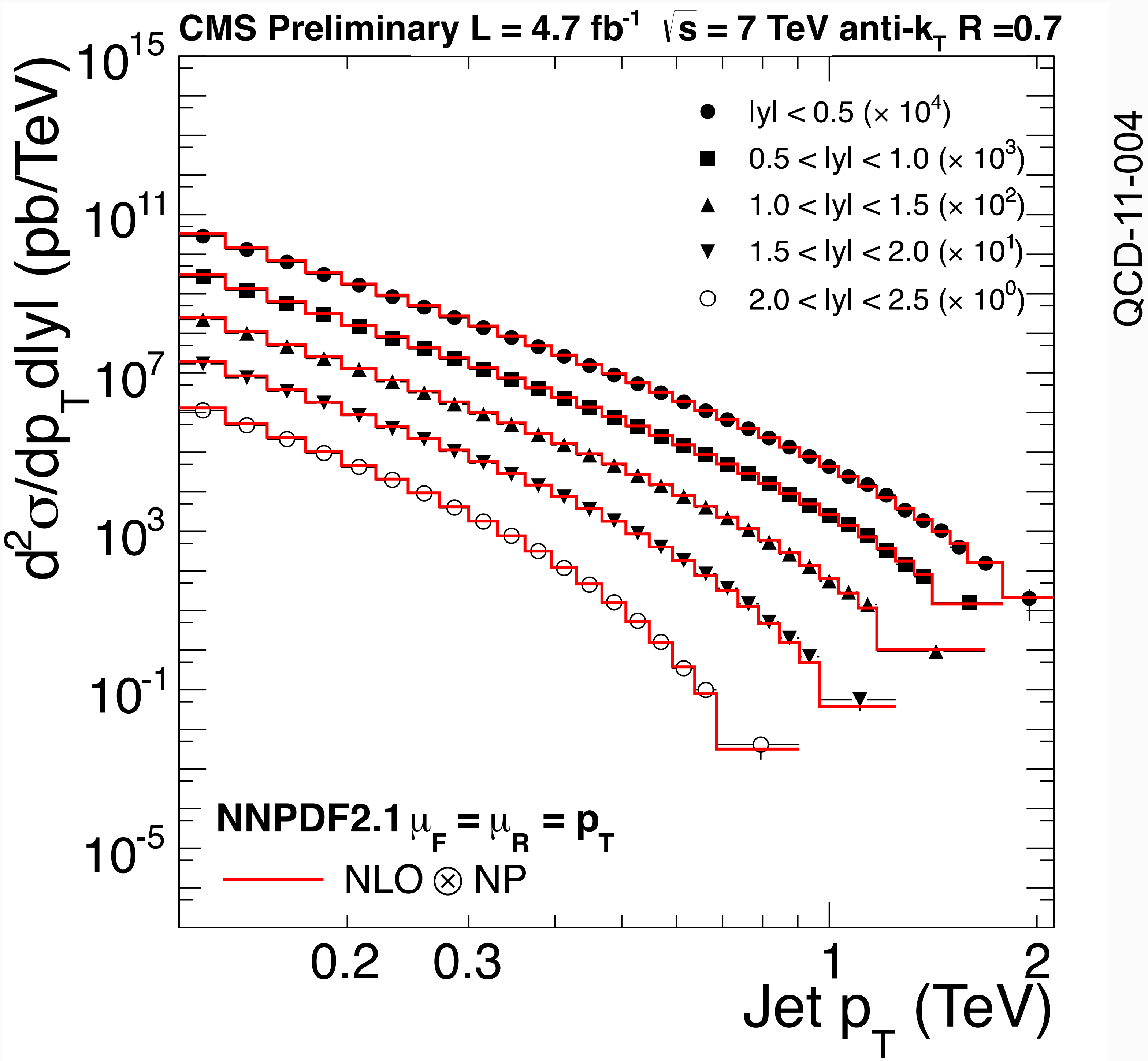


Issues for Jet Observables

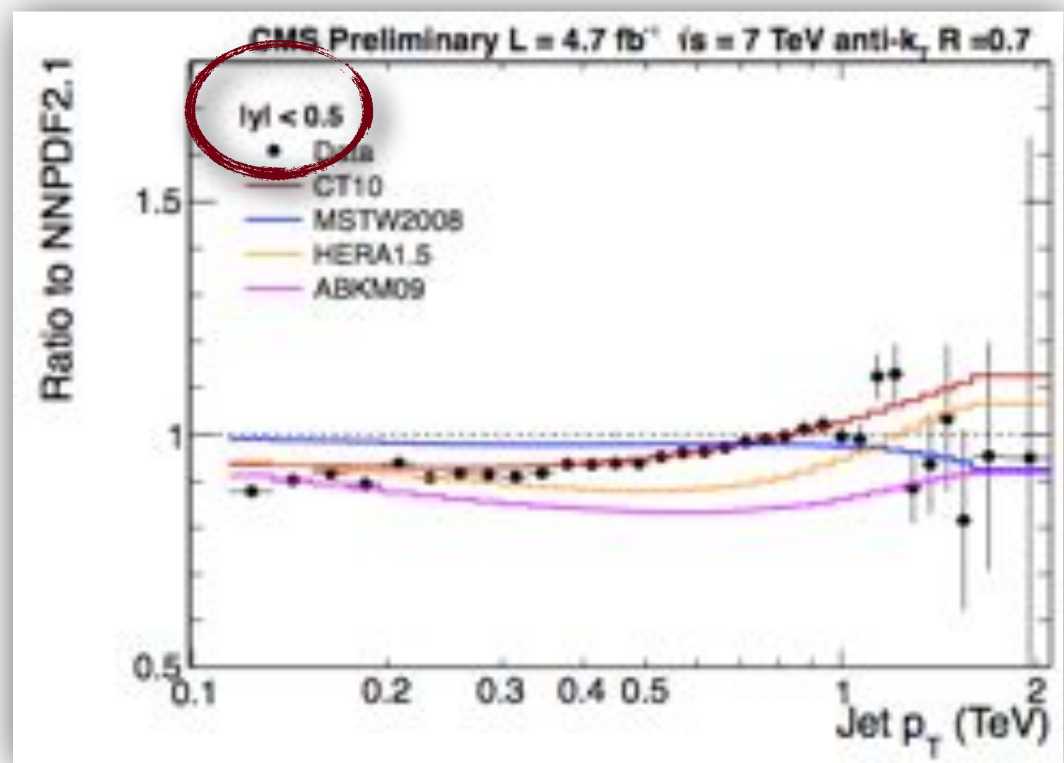
- Jet Triggers and Jet selection
  - turn-on curves, lower p_T-thresholds, matching of samples from different triggers
- Choice of Jet algorithm and jet size
  - use of modern, IR- and collinear safe algorithms
  - standard in CMS: anti-KT, R=0.5, 0.7
- Jet Energy Scale
  - absolute and relative (as function of rapidity)
  - jet cross section falls like power law, power =5 - 6
  - fantastic progress made so far, already better than 3%, hoping to achieve 1%
- Jet Energy resolution
  - smearing of distributions
- Comparison with theory at the “hadron (or particle) level” : correction of pQCD prediction for non-pert. effects
- Often “ratio” observables used to reduce dependence on jet energy scale: di-jet ratio, angular (de-)correlations, event shapes, n-jet ratios, jet shapes, ...
  - however, the use of a p_T threshold above which jets are selected introduces a dependence !

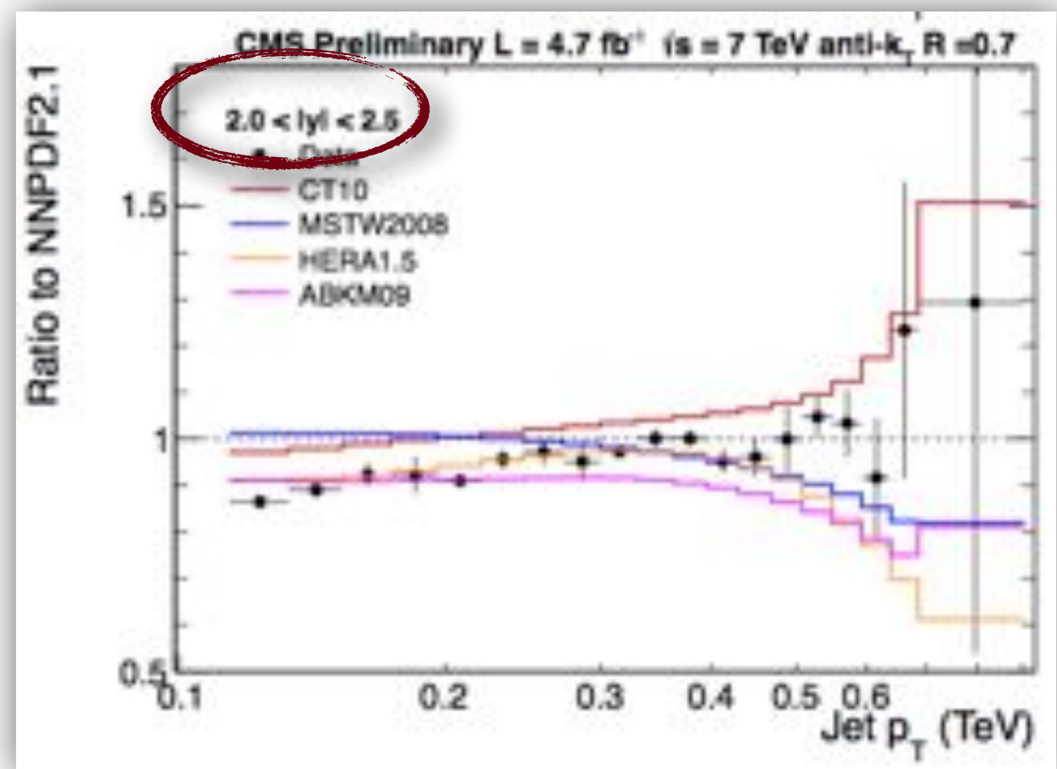
Inclusive jet cross section

- up to p_T ~ 2 TeV !
- Earlier measurements extended to very low p_T thanks to Particle Flow
- JES uncertainties dominating exp. uncert.
- Corrected to particle level
- Inclusive jet p_T spectra are in **good agreement with NLO QCD**
- exp. precision starting to be interesting to constrain pdfs

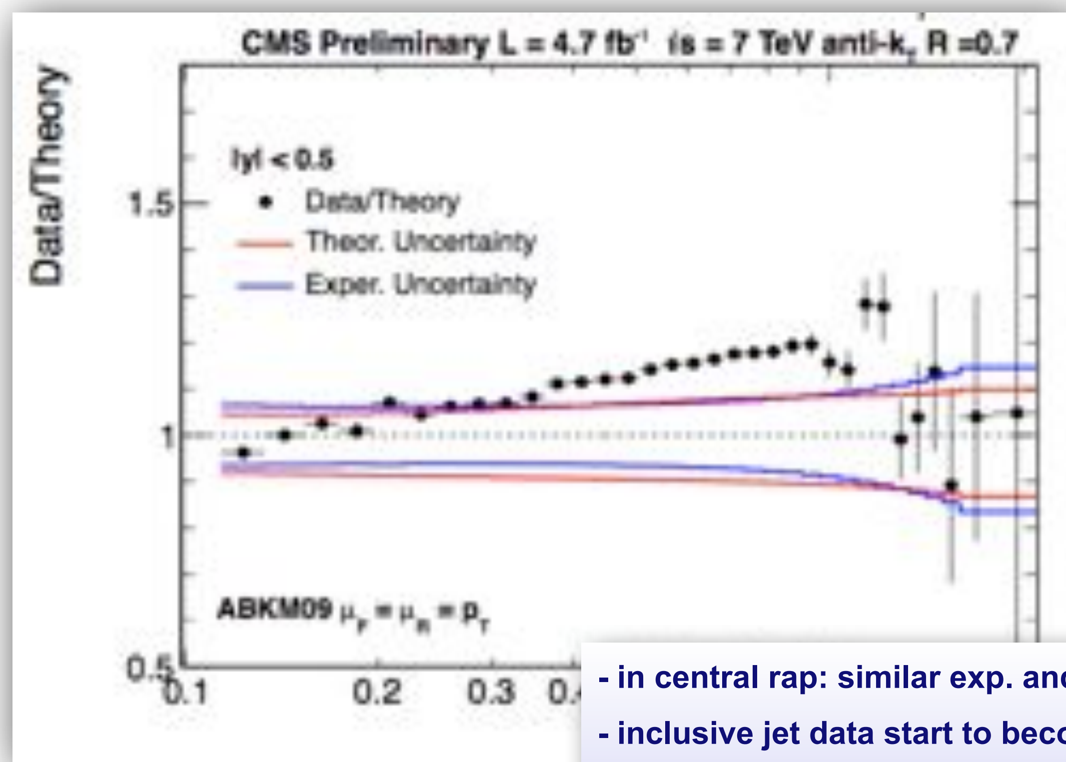


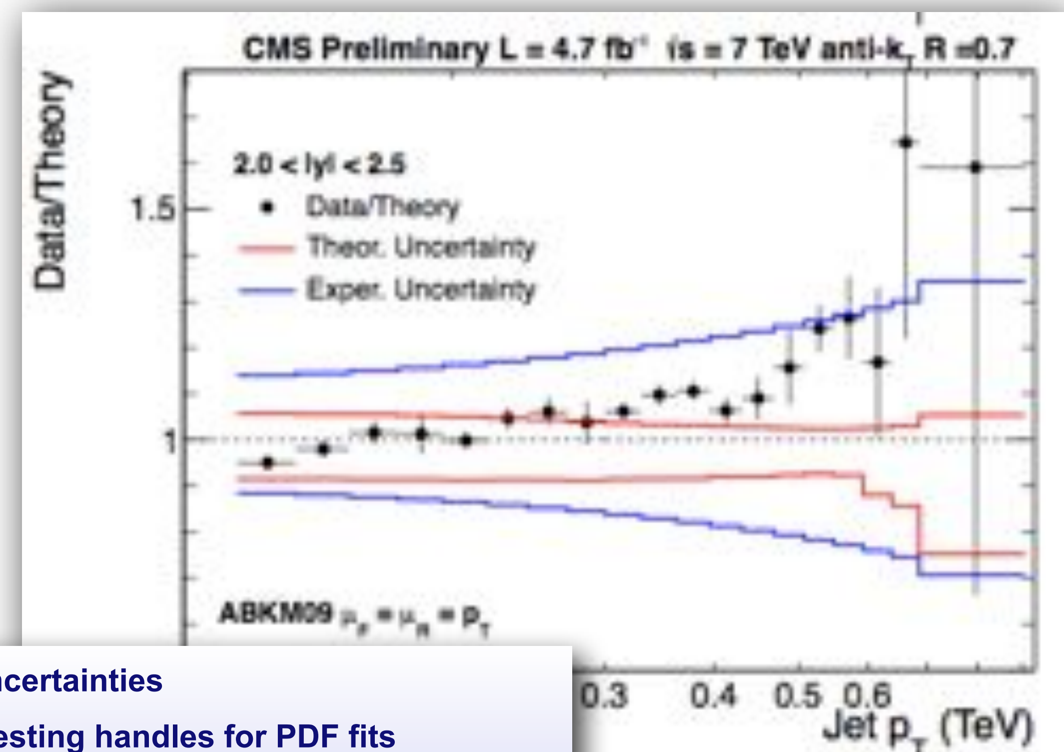
More comparisons to PDFs...





More details: see CMS PAS QCD-11-004



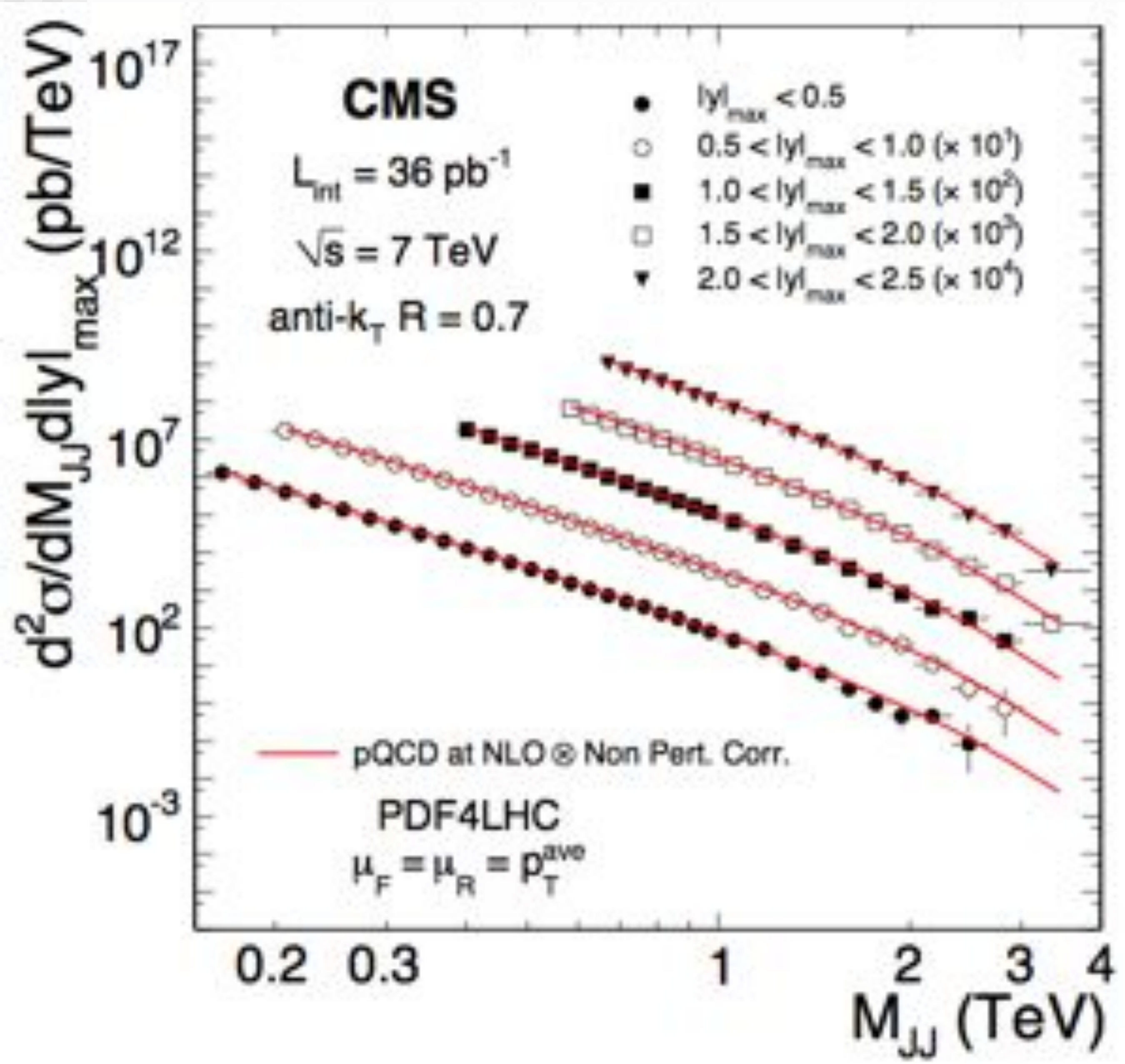


- in central rap: similar exp. and theo. uncertainties
- inclusive jet data start to become interesting handles for PDF fits
- central jets: CT10 fine. More forward: DIS-based PDFs (HERA1.5,ABKM) do better (sensitive to low-x gluon)

Di-jet distributions

ETH Institute for Particle Physics

Di-jet mass distribution



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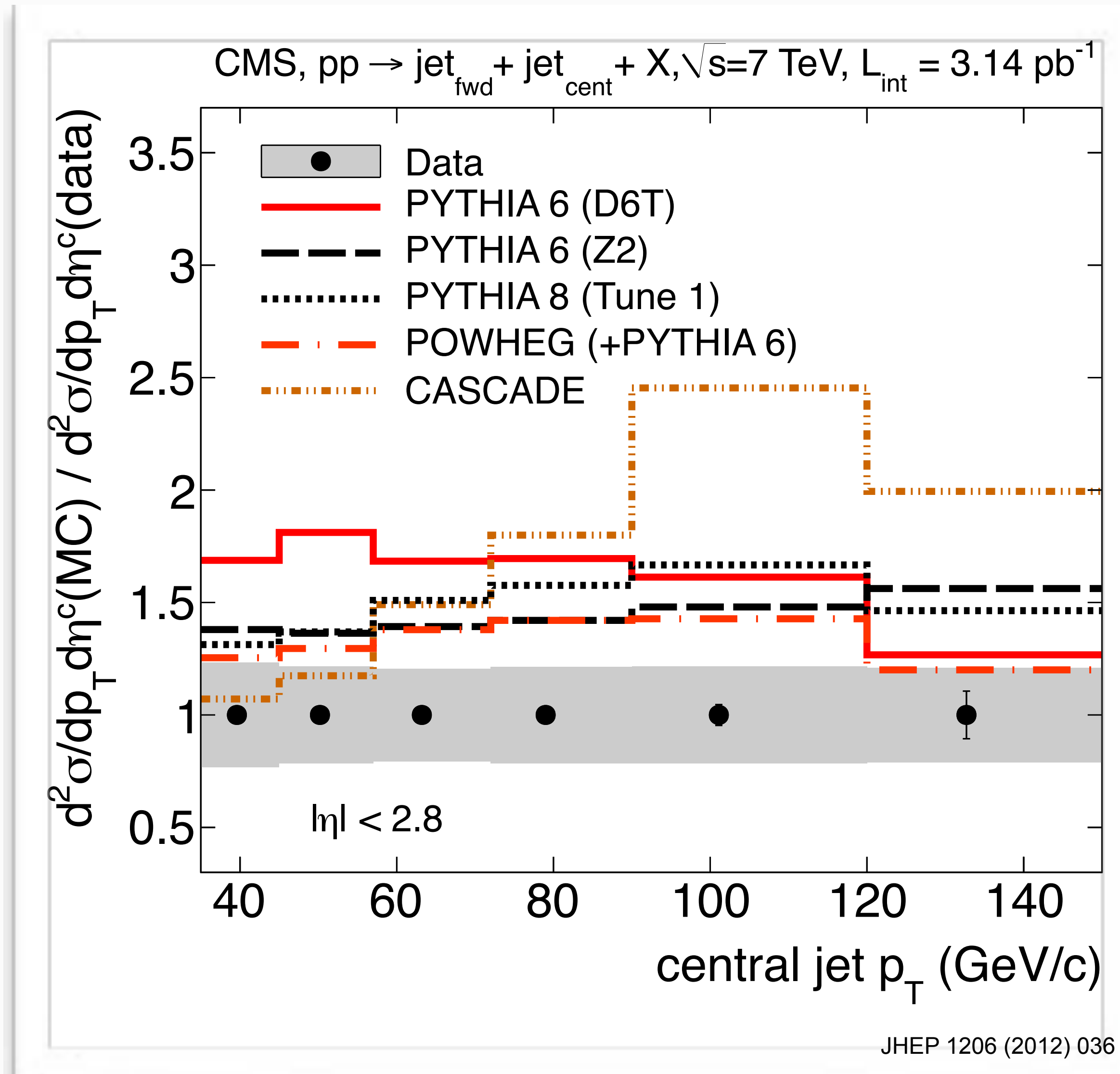
- All distributions unfolded/corrected for detector effects

Overall, pretty good agreement with NLO QCD

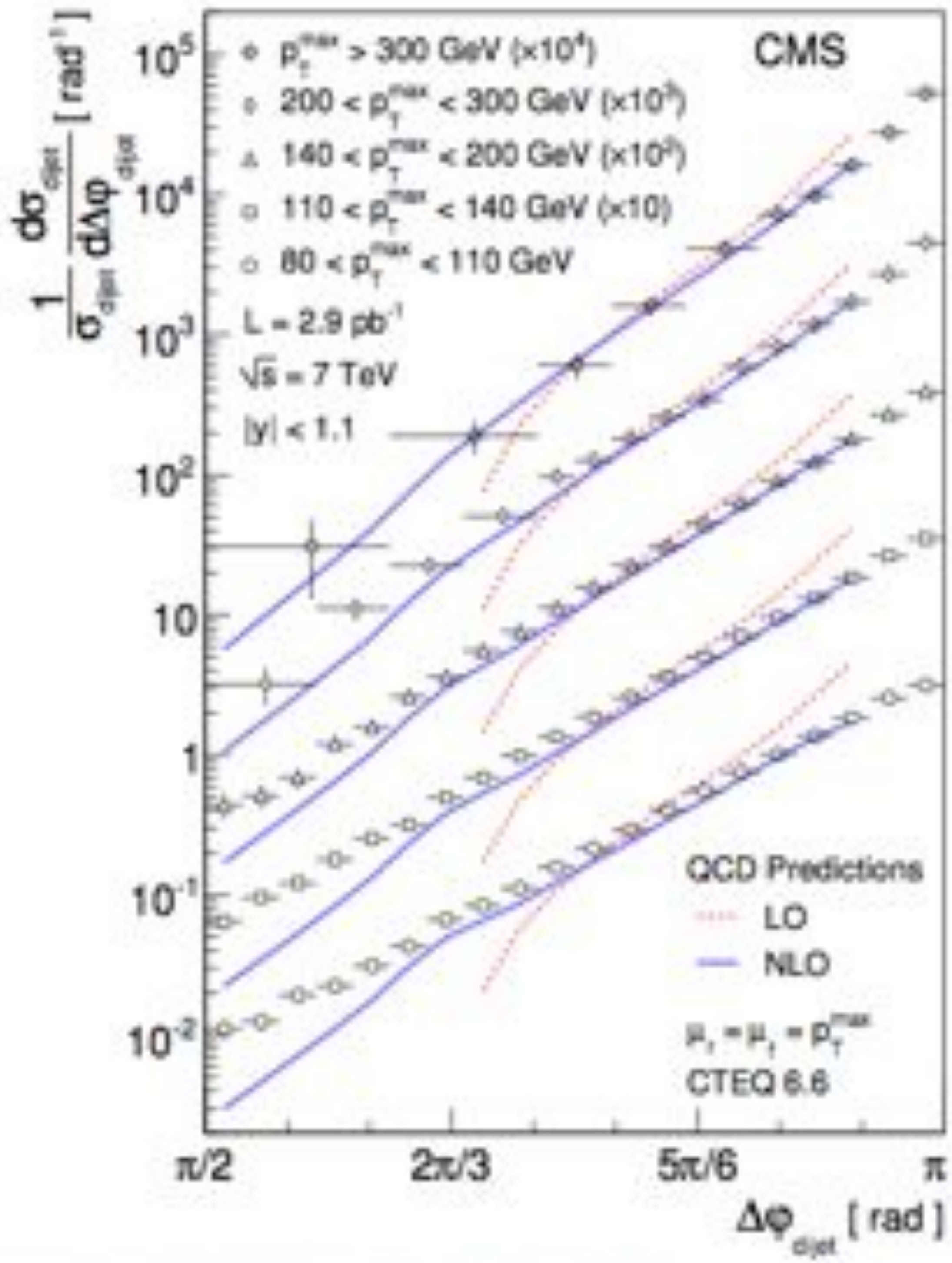
However:

Requiring both a central and forward jet at the same time causes **disagreement for a number of models.**



Correlations in Azimuth

- Independent of luminosity, weakly dependent on Jet Energy Scale



$$\Delta\phi \sim \frac{\pi}{2} \qquad \Delta\phi \sim \pi$$

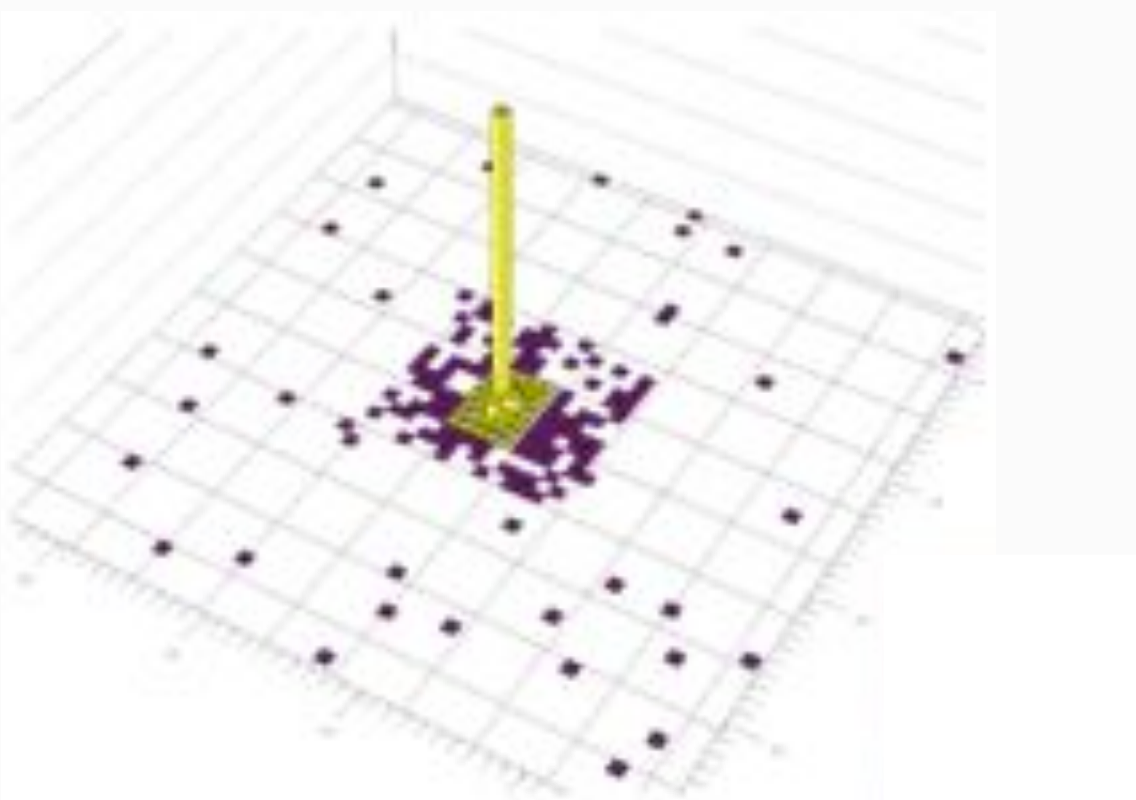
✦ **Normalized dijet cross section, as a function of Δφ**
  - indirect probe of multijet topologies, without explicit reconstruction of additional jets

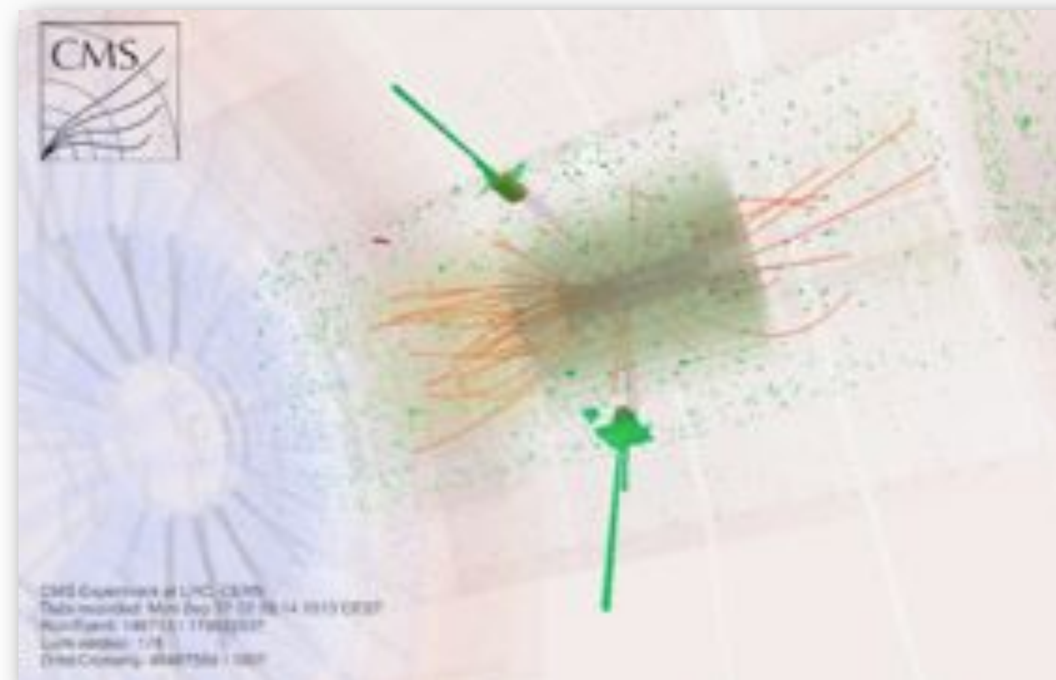
✦ **pQCD @ NLO is necessary to describe the azimuthal decorrelation**

PRL 106 (2011) 122003

CERN EP/PP Seminar "*QCD Results from CMS*" Konstantinos Kousouris 35

Production of Photons

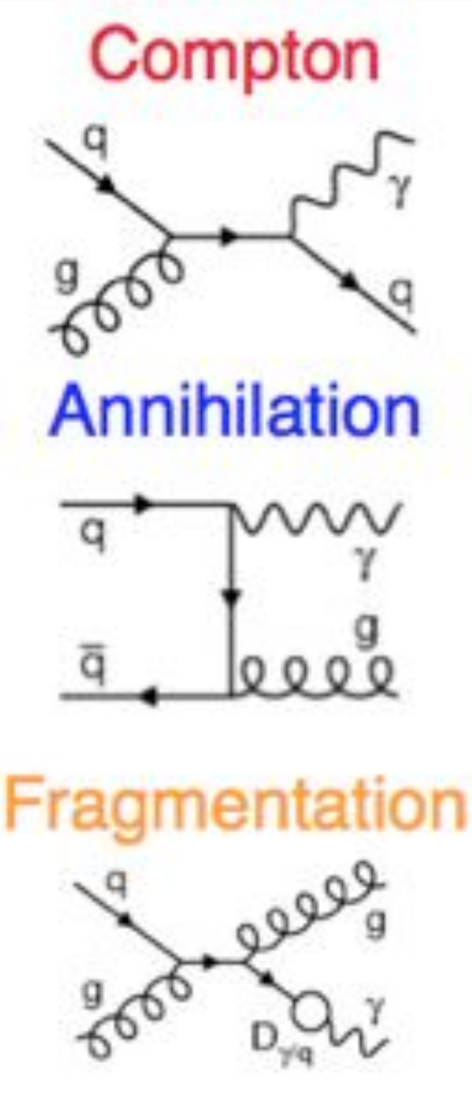


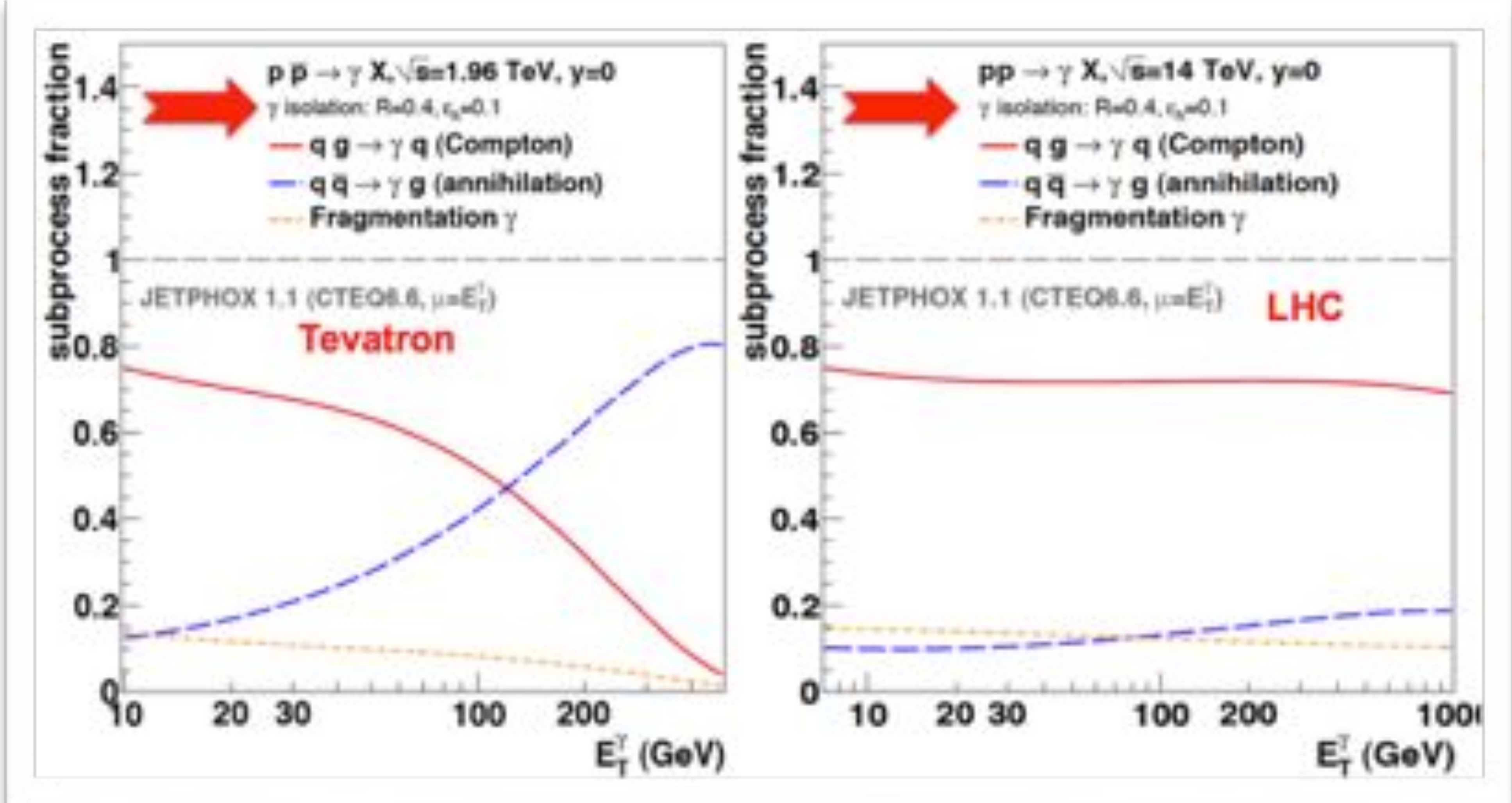


Direct Photon Production

ETH Institute for Particle Physics

slide adapted from K. Kousouris



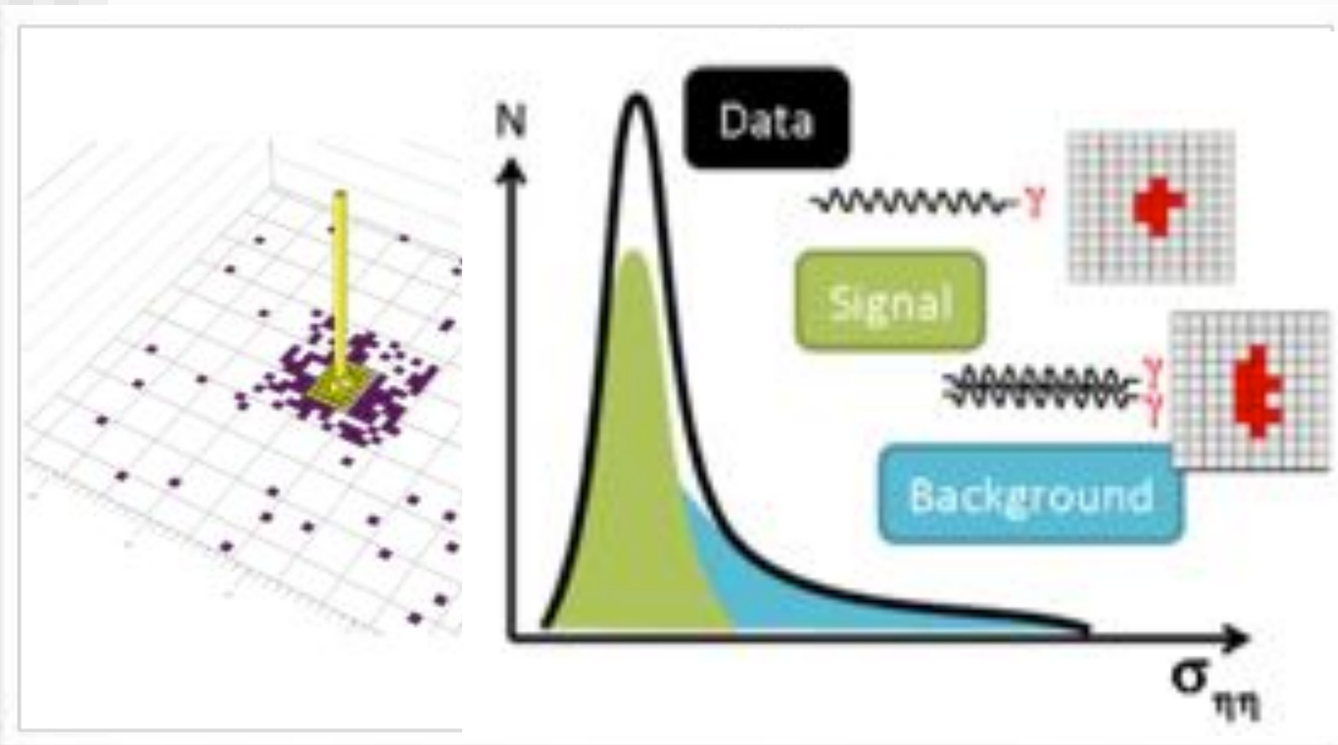


- Important issue
  - fragmentation contribution
  - can be strongly suppressed by isolation requirements
  - theoretically most interesting: Frixione isolation, but not exactly implementable in exp. analyses... many studies ongoing

Photon Identification

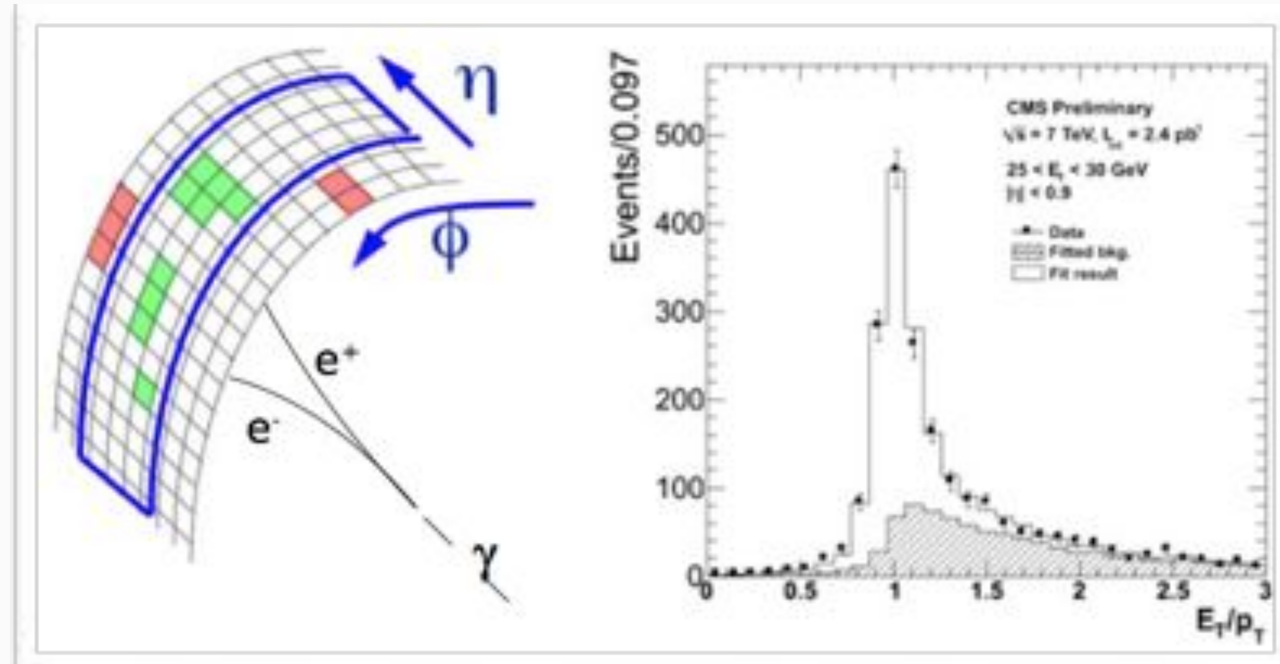
slide adapted from K. Kousouris

templates, on isolation or cluster shape variables



powerful at high E_T

Conversions

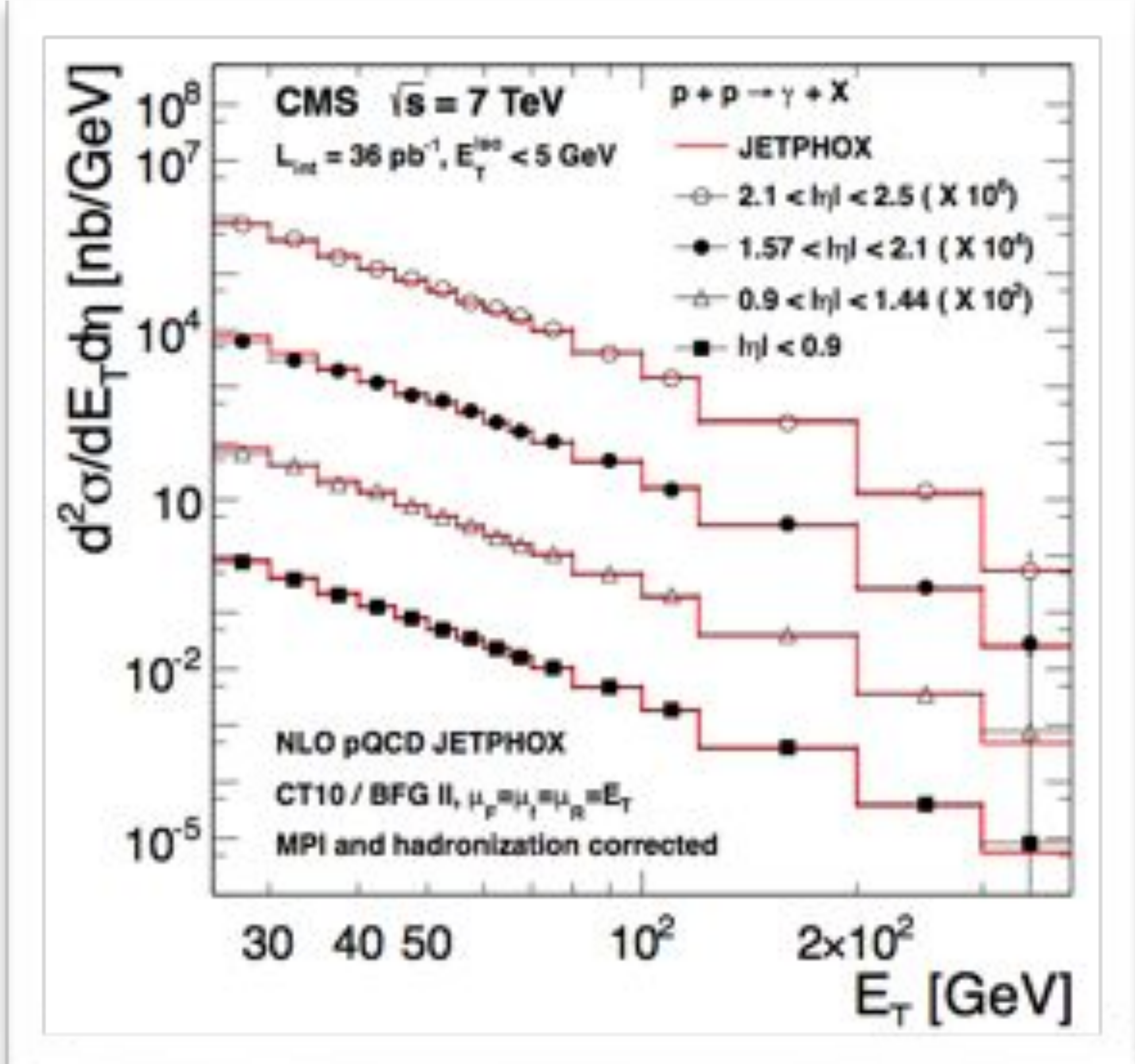


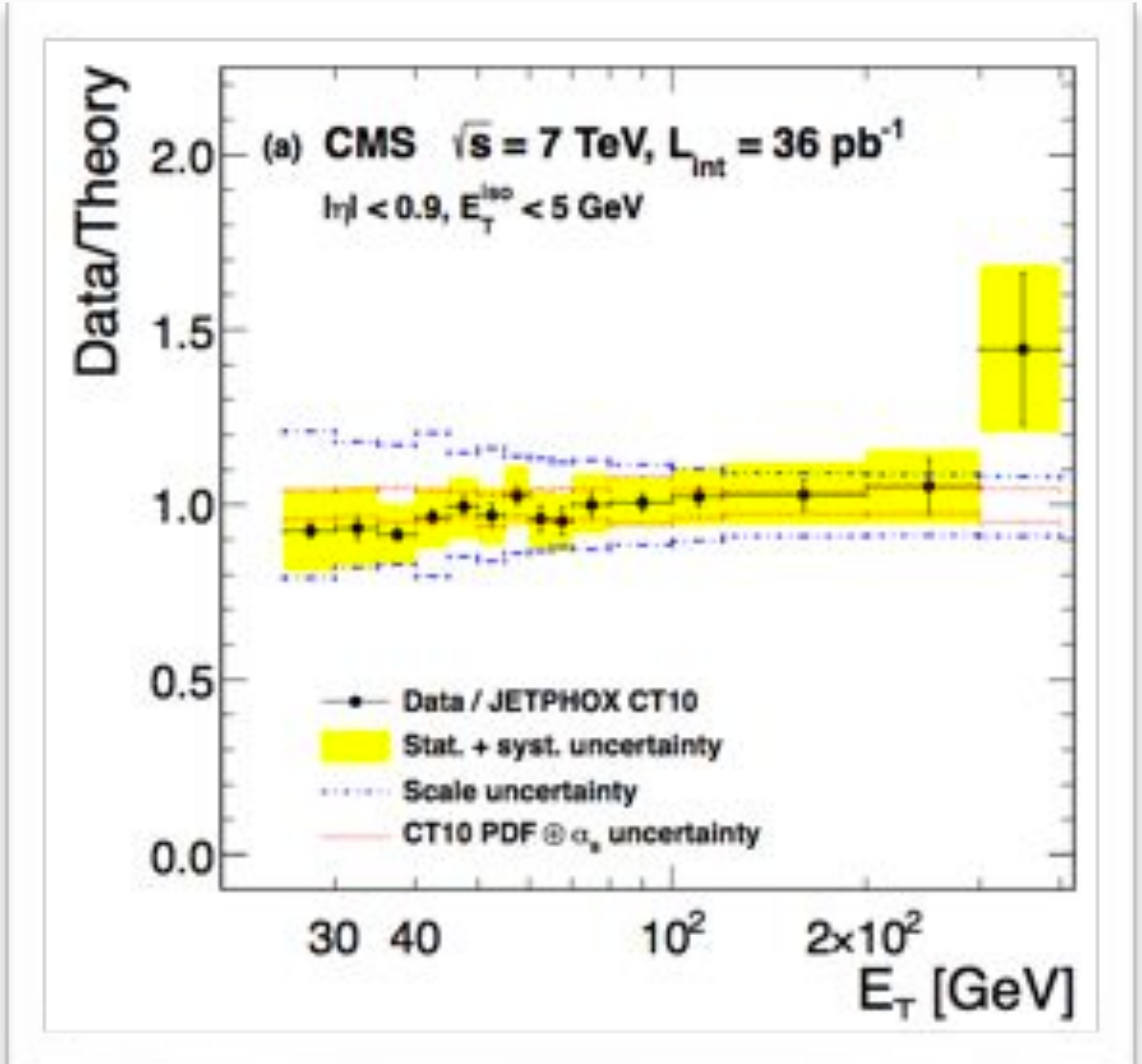
powerful at low E_T

- **Typical efficiencies**: ~100% (trigger), ~85% (reco barrel), ~75% (reco endcap), ~60 – 90% (identification & isolation), Unfolding (bin migrations): ~95%
- **Systematic uncertainties** on the order of 15% or below

Inclusive Production: Results

PRD 84 (2011) 052011



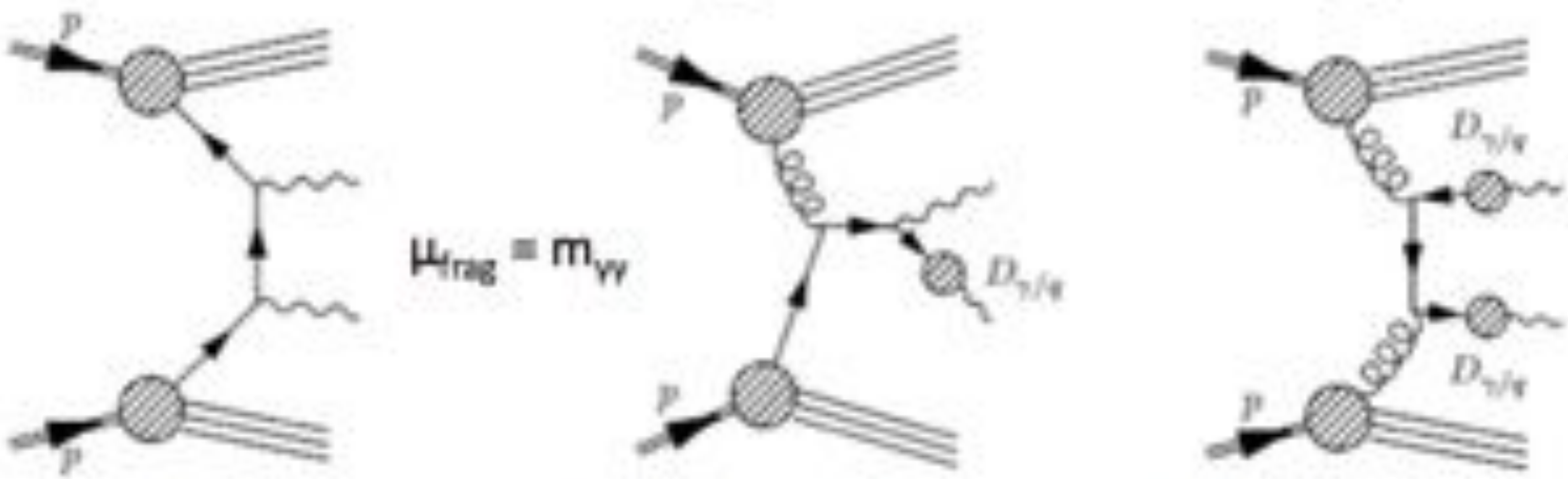


Overall, pretty good agreement with NLO QCD
Slight overprediction at $E_T < 50$ GeV ?

Di-Photon Production

slide adapted from K. Kousouris

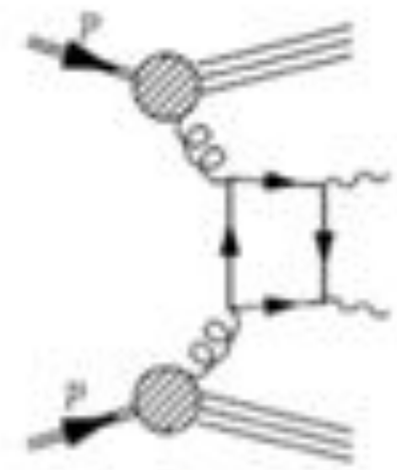
Direct Born | **One Fragmentation** | **Two Fragmention**



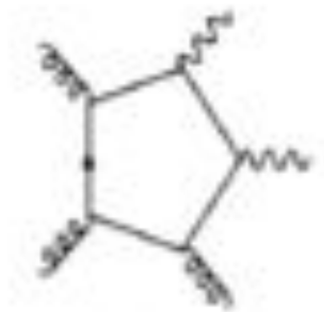
26 pb @ NLO | 10 pb @ NLO | 0.5 pb @ NLO

DIPHOX

Direct Box



15 pb @ NLO

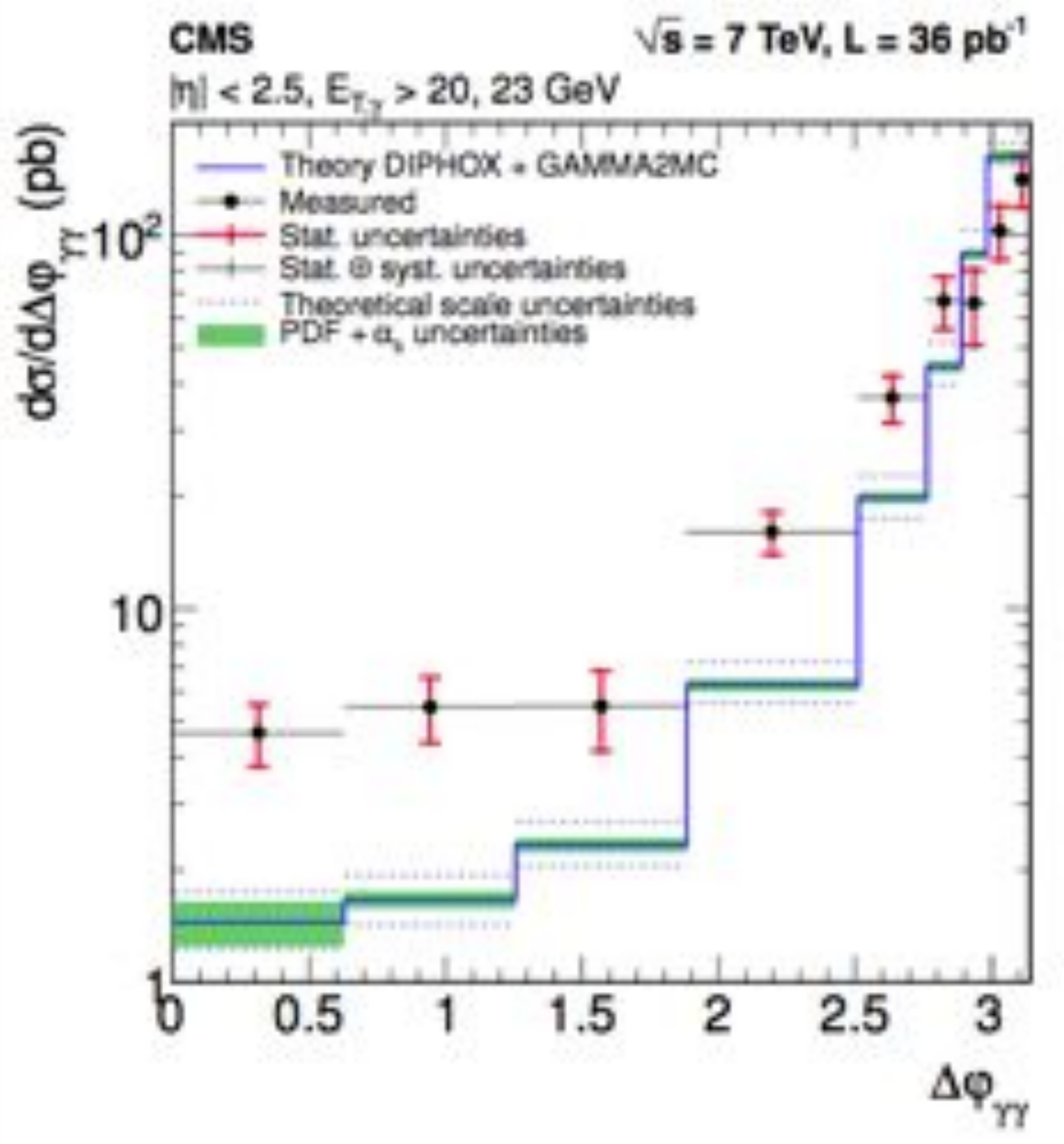


GAMMA2MC

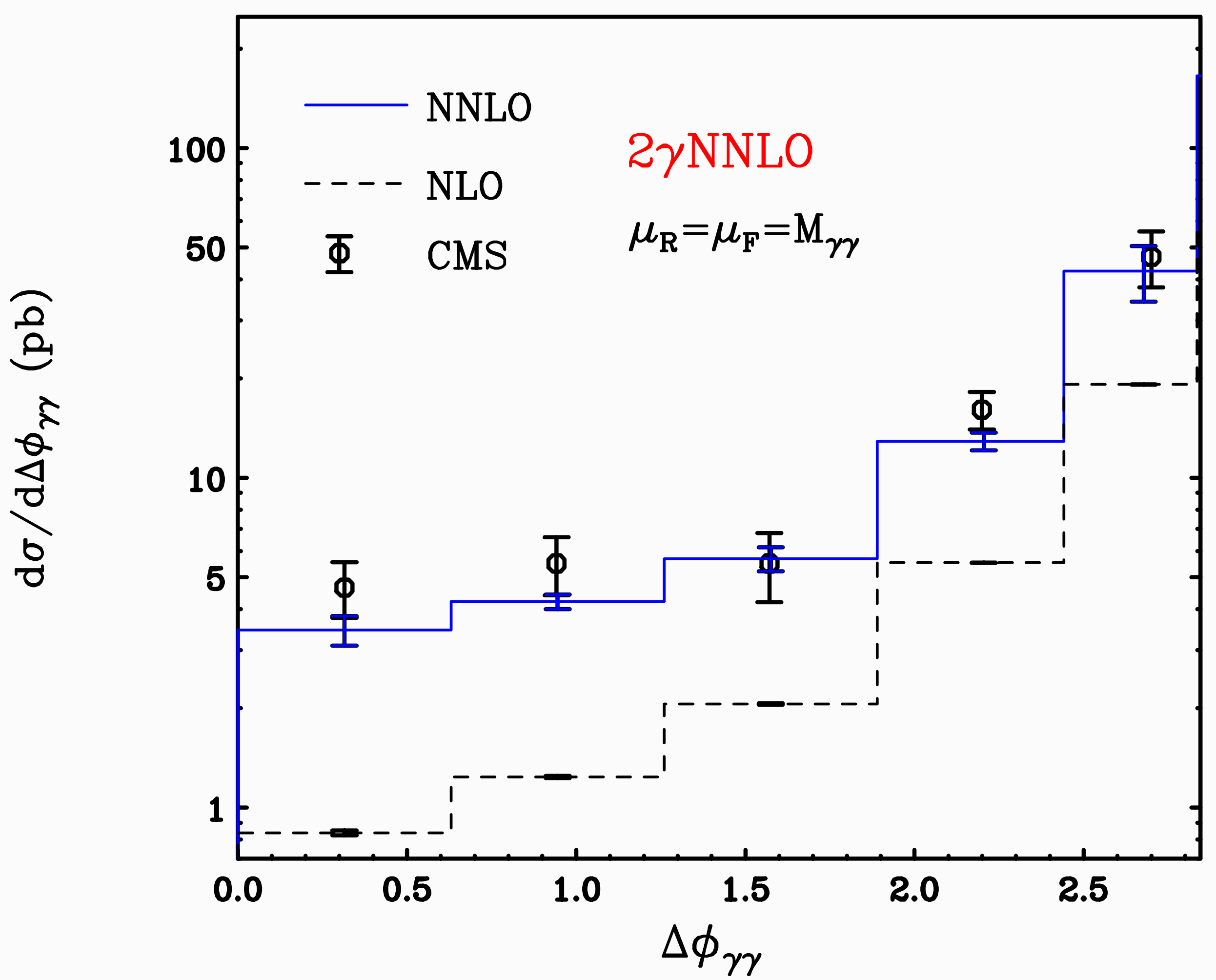
- **Probing pQCD**
  - NLO calculations
  - PDF
- **Irreducible background for the H→γγ search**

Di-Photon Production: Results

JHEP 01 (2012) 083



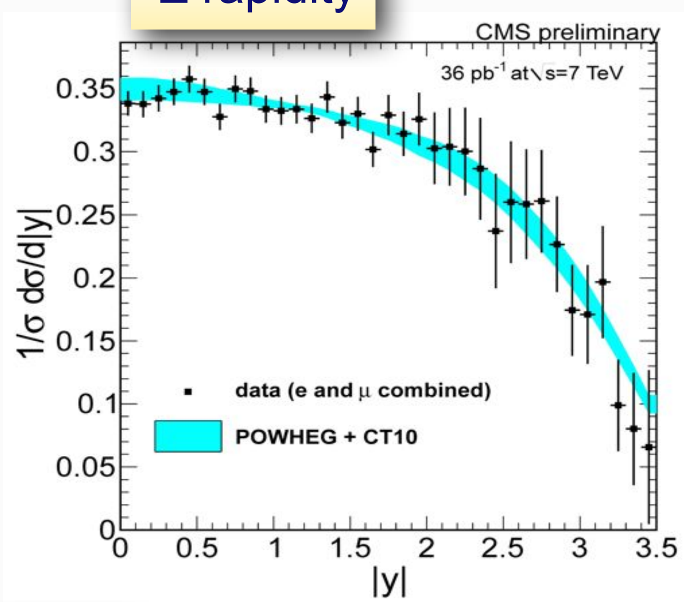
from D. de Florian, M. Grazzini, et al



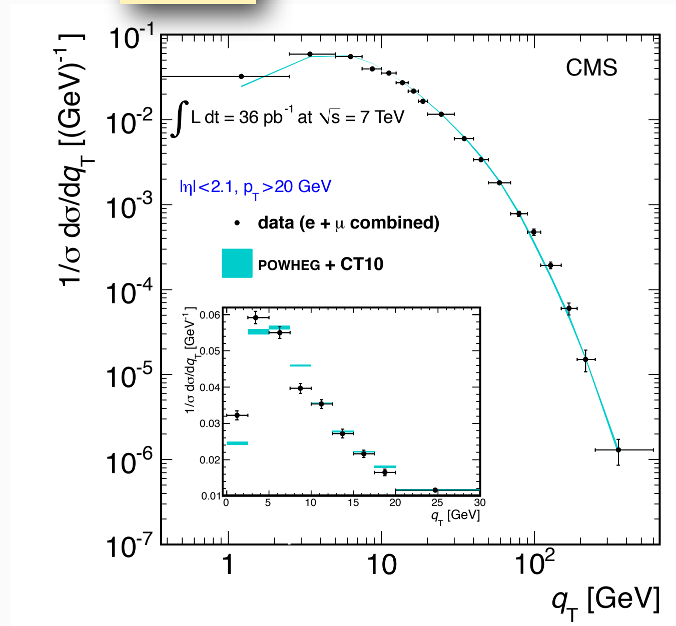
- **Big discrepancy at small angles???**
  - But note: at very small angles, the NLO calculation is actually a “LO” calculation
  - confirmed by very recent NNLO calculation (see plot on the right)

Production of Vector Bosons

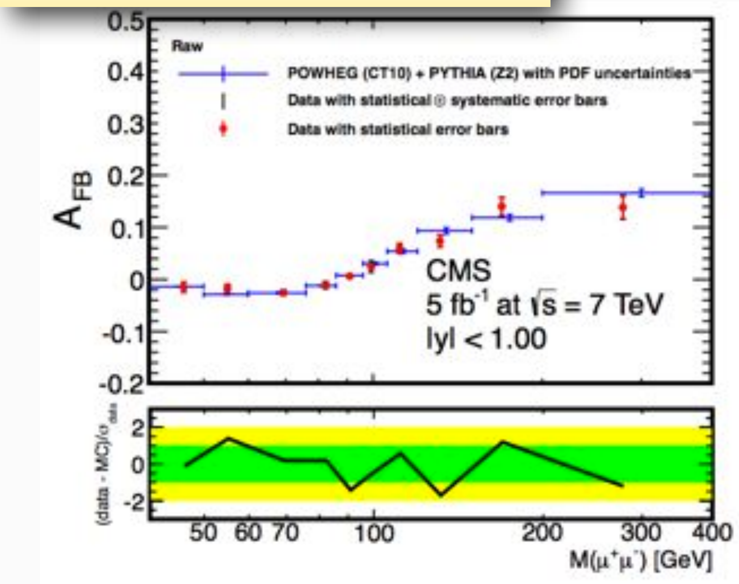
Z rapidity



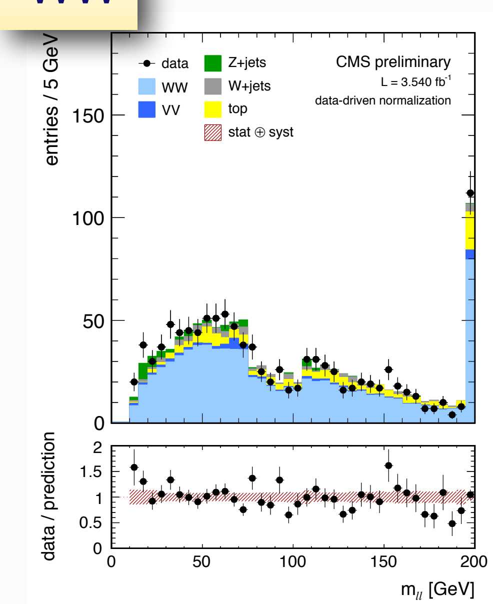
Z p_T



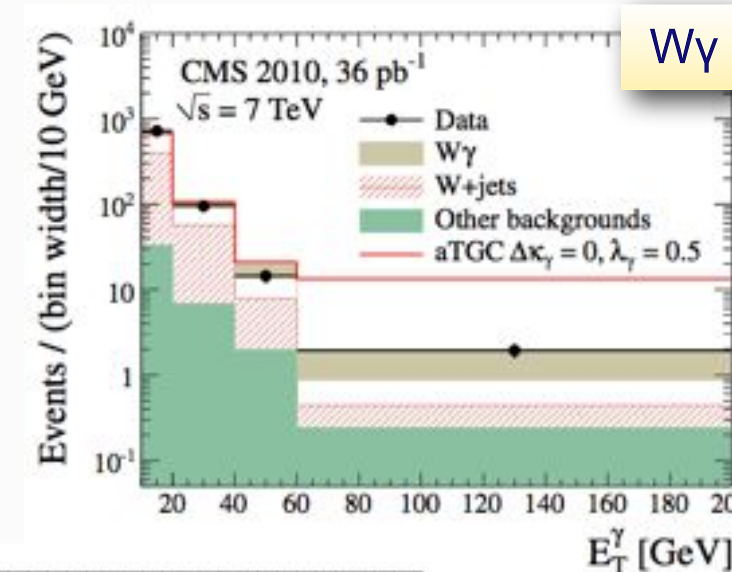
DY fwd-bkw asymmetry



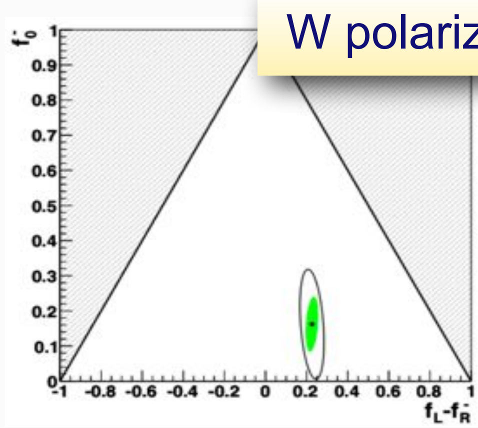
WW



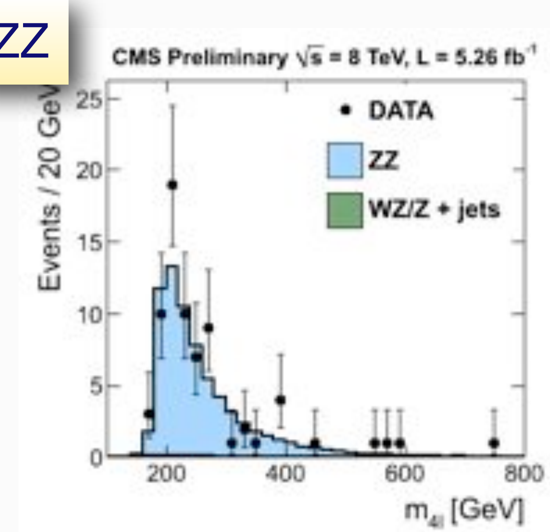
Wγ



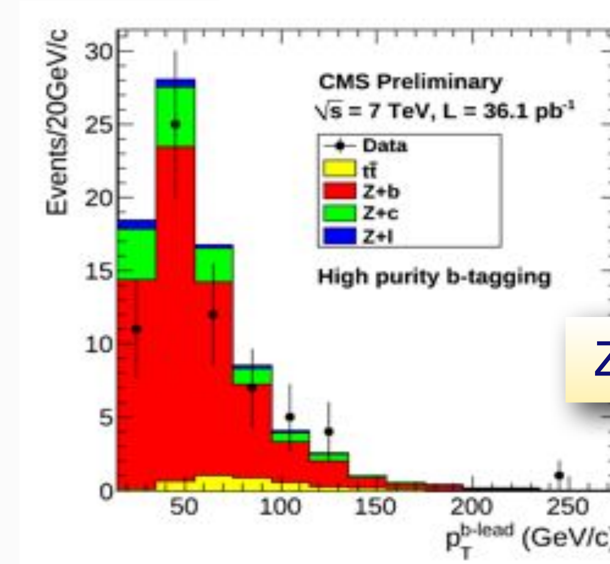
W polarization



ZZ

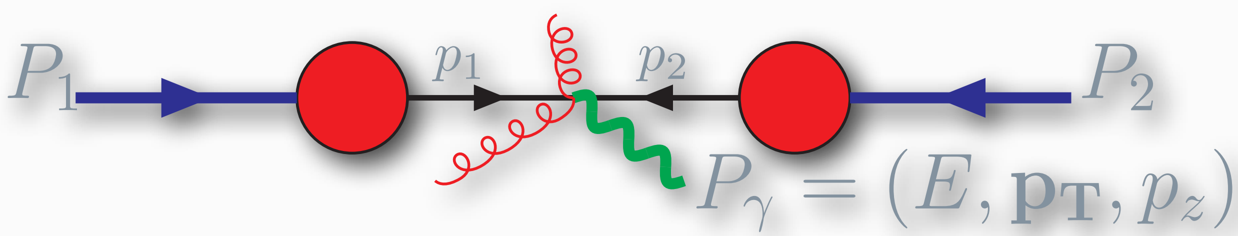


Zb



Predictions

known up to NNLO in pert. QCD!



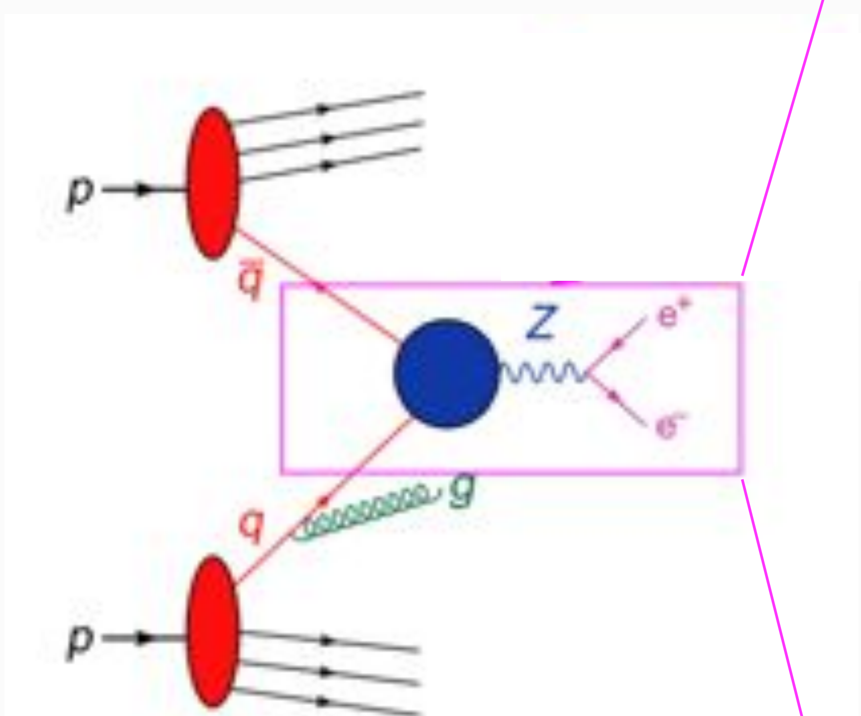
Using FEWZ and MSTW2008, at 7 TeV:

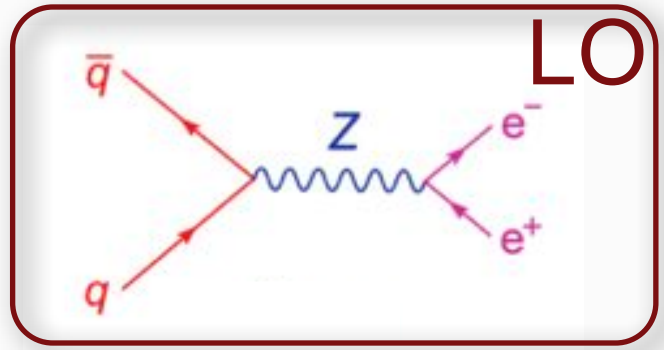
$$\sigma^{NNLO}_{W^+\to\ell^+\nu} = 6.16 \text{ nb}$$

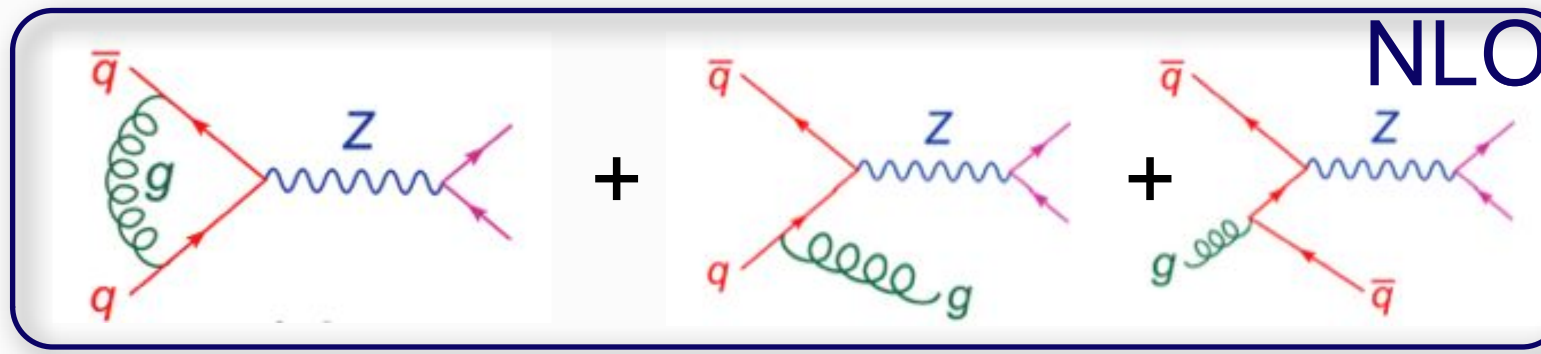
$$\sigma^{NNLO}_{W^-\to\ell^-\bar{\nu}} = 4.30 \text{ nb}$$

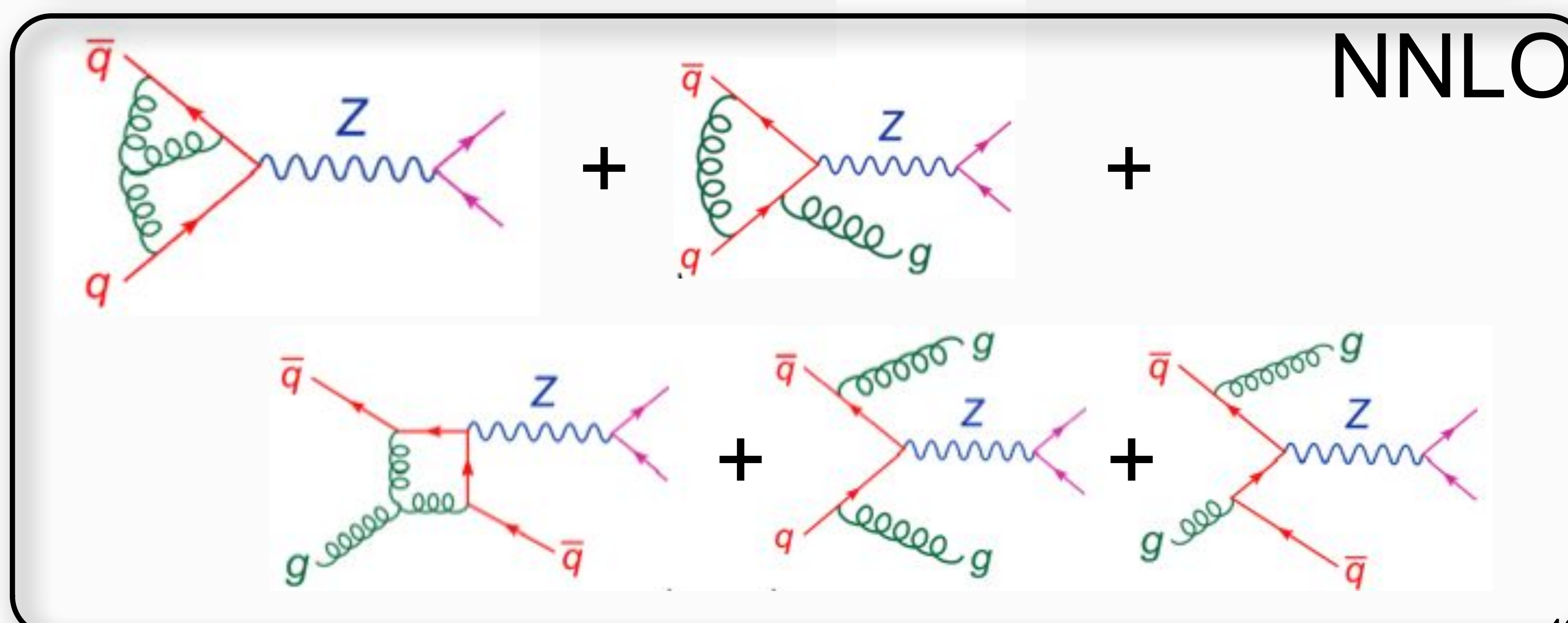
$$\sigma^{NNLO}_{Z/\gamma^*\to\ell\ell} = 0.96 \text{ nb}$$

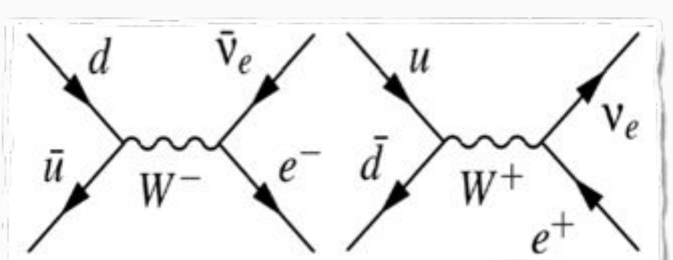
with very small scale uncertainties (< 1%) and PDF uncertainties of O (5%)





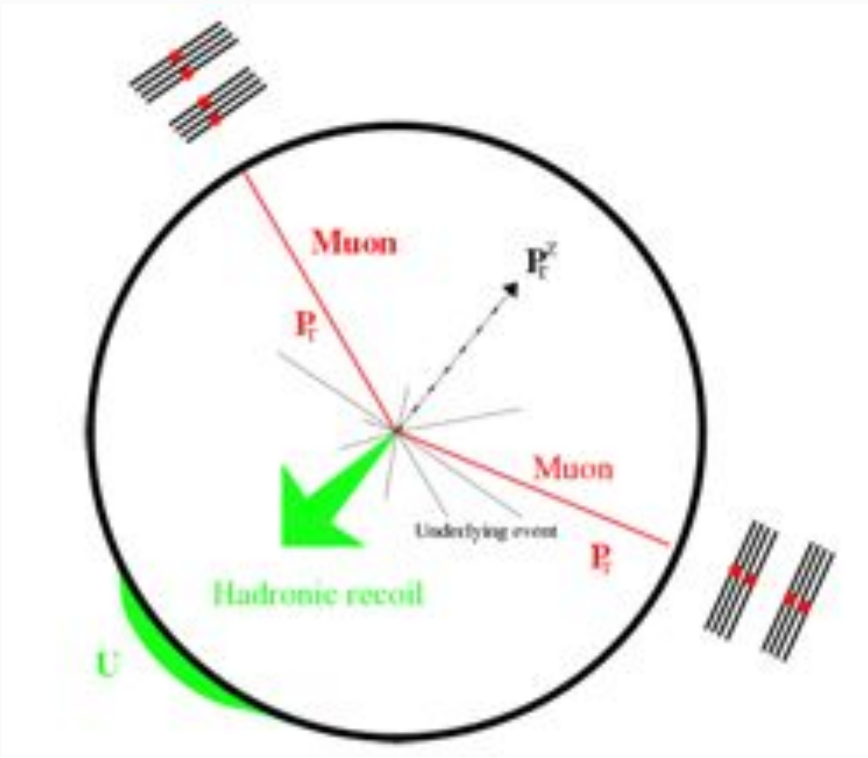




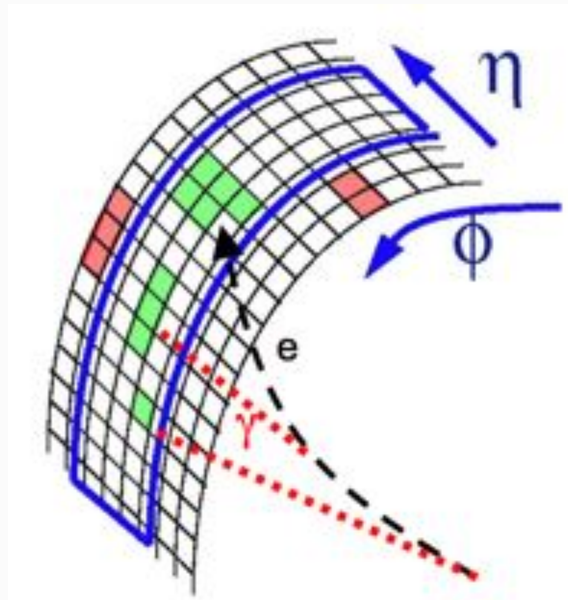


Produce more W+ than W- (prevalence of u quarks over d quarks).

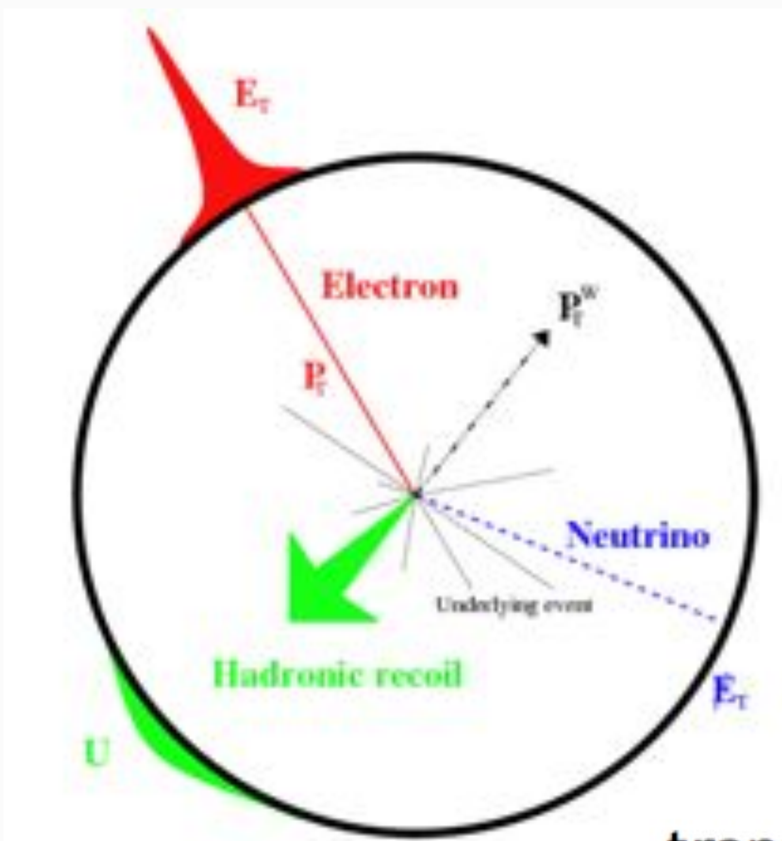
Experimental signature



Z: pair of charged leptons
- high-p_T (> 20 GeV)
- isolated
- opposite charge
- ~60 < m_{ll}< ~120 GeV



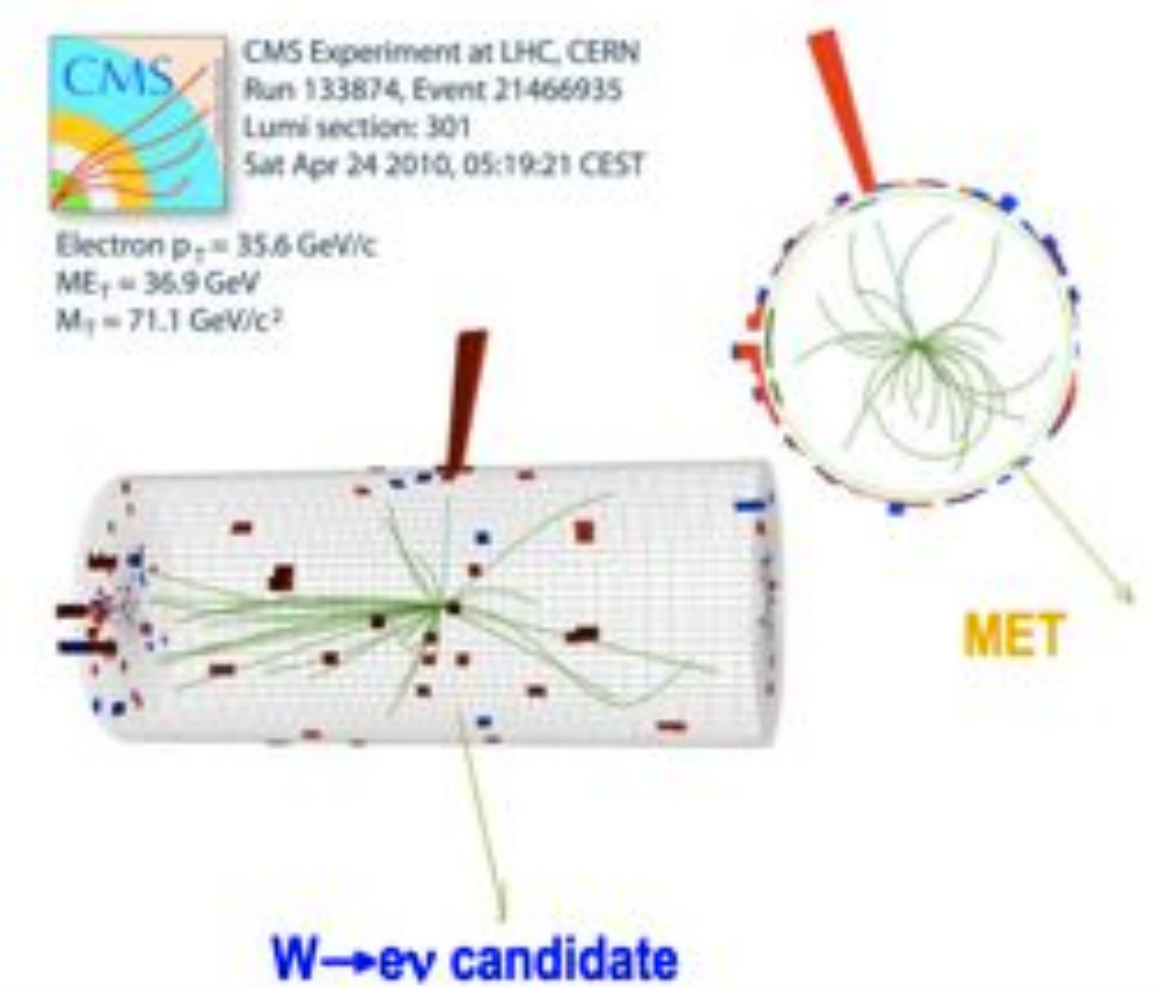
Example: electron reconstruction
- isolated cluster in EM calorimeter
- p_T > 20 GeV
- shower shape consistent with expectation from electrons
- matching charged track

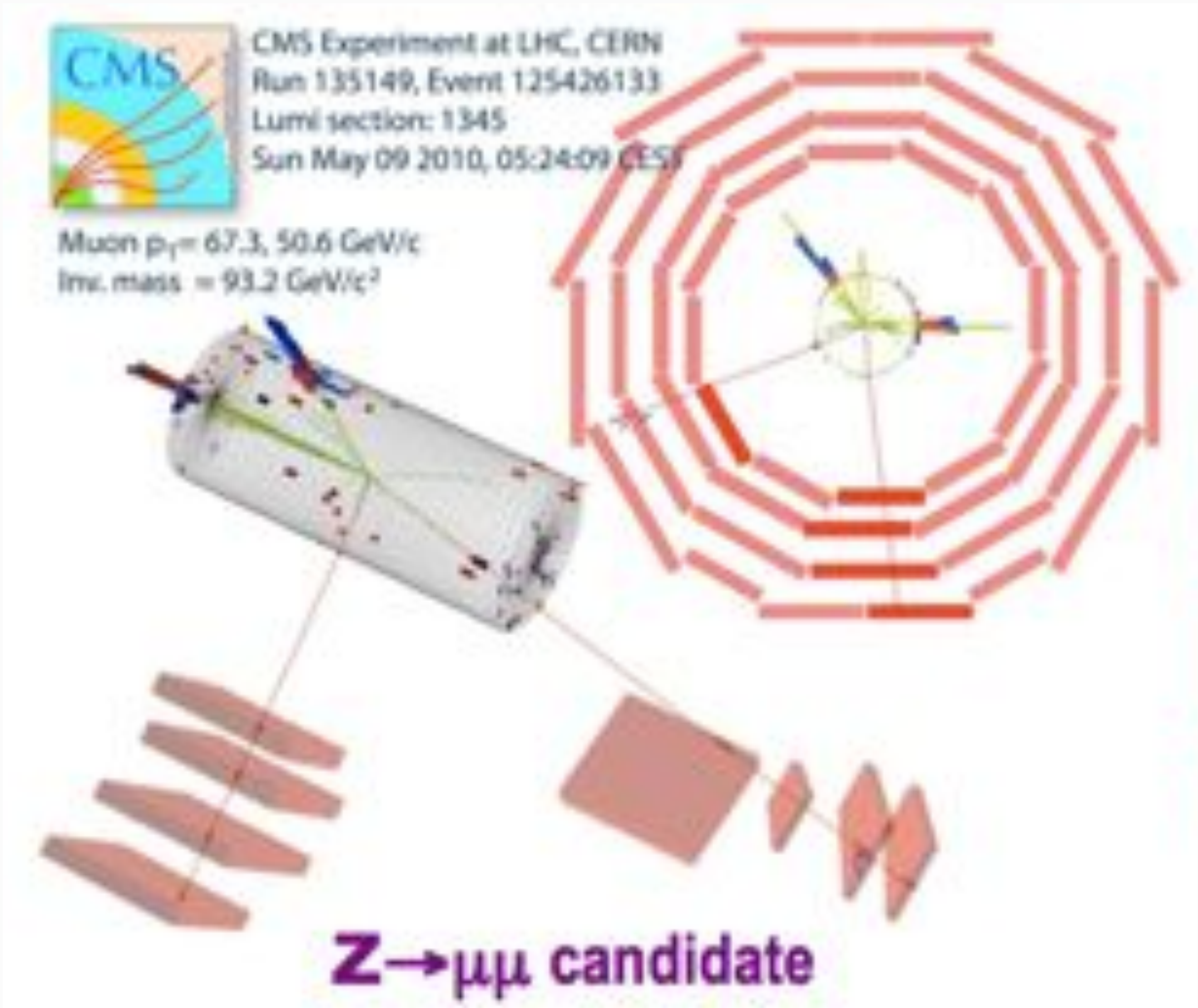


W: single charged leptons
- high-p_T (> 20 GeV)
- isolated
- $E_{T,miss}$ (from neutrino)

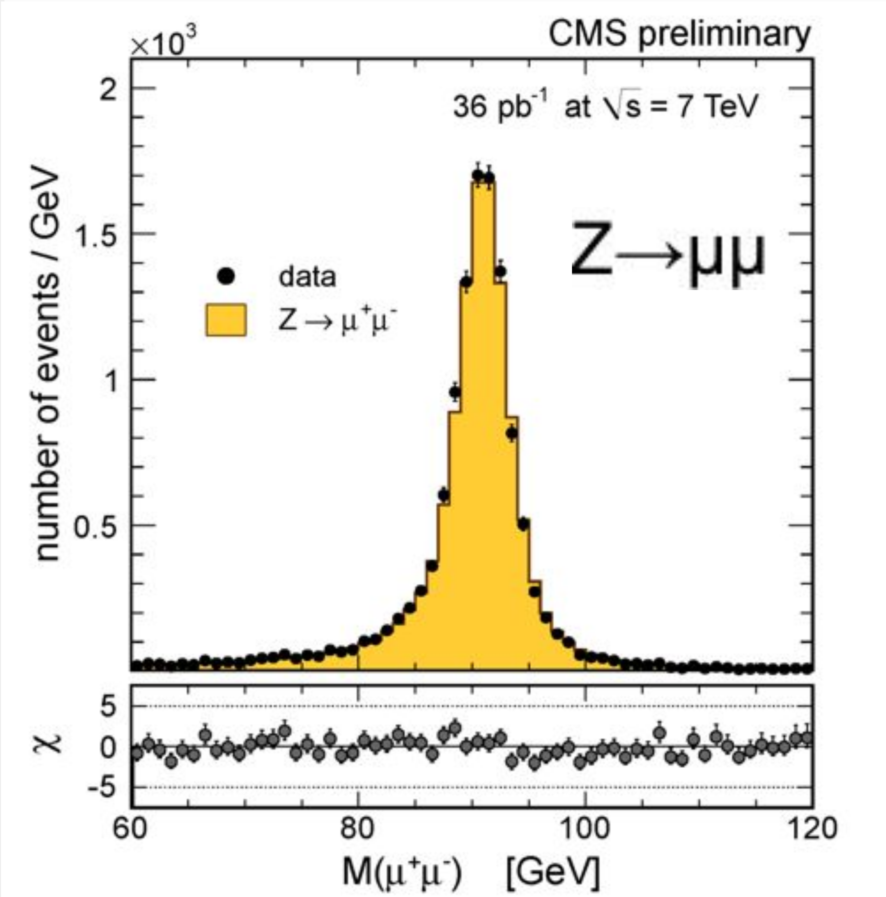
transverse mass: $M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^\nu \cdot \left(1 - \cos\Delta\phi^{l,\nu}\right)}$

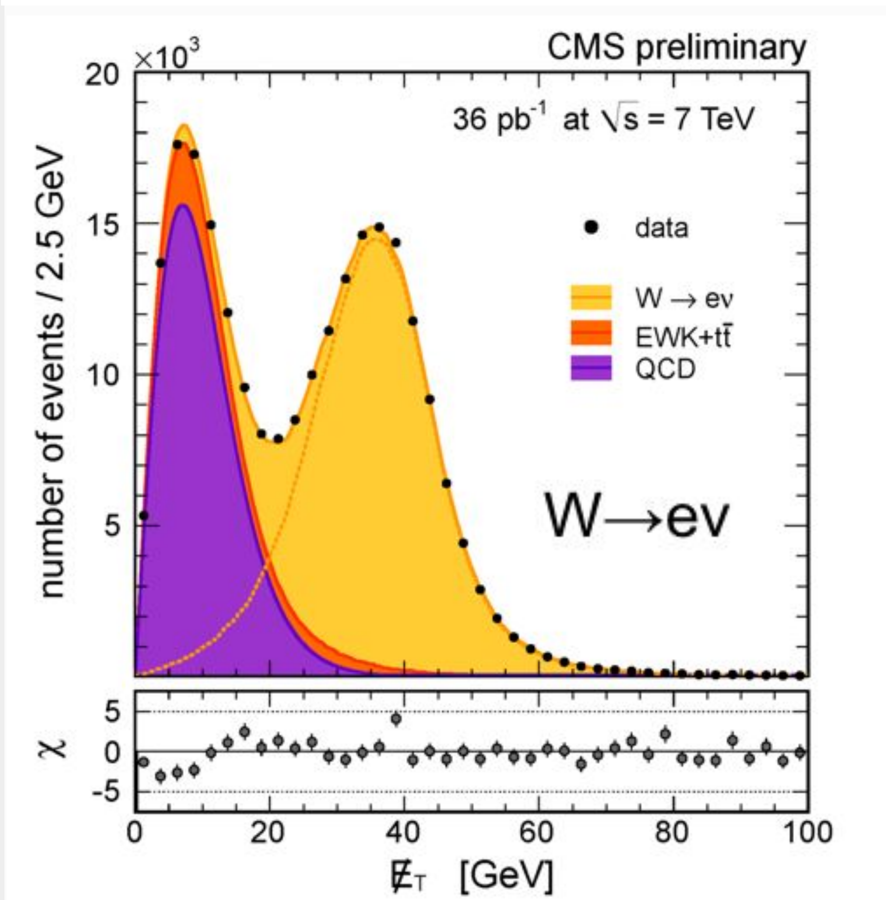
Signatures


CMS Experiment at LHC, CERN
Run 133874, Event 21466935
Lumi section: 301
Sat Apr 24 2010, 05:19:21 CEST
Electron p_T = 35.6 GeV/c
ME_T = 36.9 GeV
M_T = 71.1 GeV/c²
MET
W→eν candidate

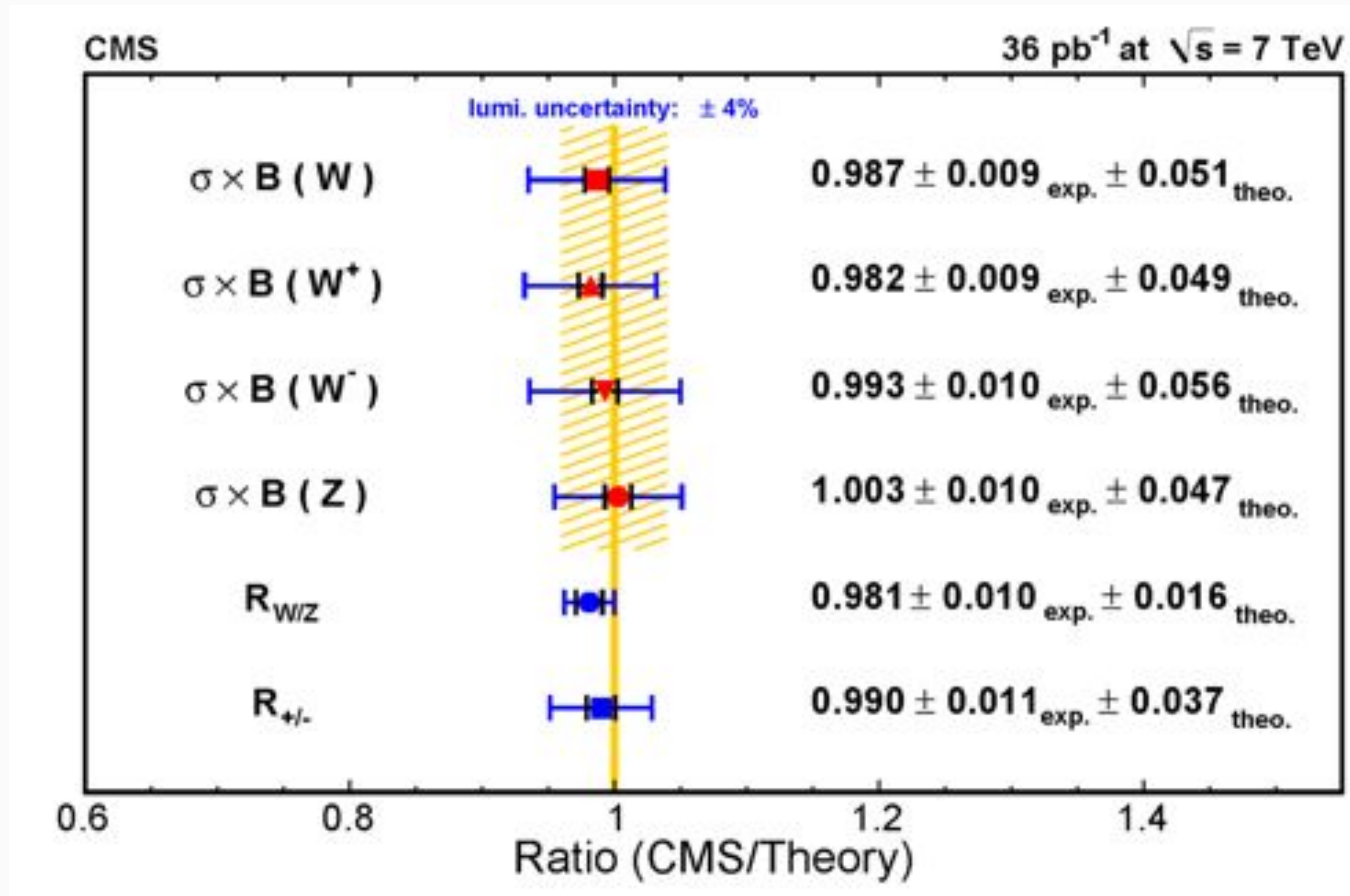

CMS Experiment at LHC, CERN
Run 135149, Event 125426133
Lumi section: 1345
Sun May 09 2010, 05:24:09 CEST
Muon p_T = 67.3, 50.6 GeV/c
Inv. mass = 93.2 GeV/c²
Z→μμ candidate

Inclusive W and Z production





- Z important tool : data-driven methods for controlling lepton eff, scale, resolution, E_{Tmiss} (hadronic recoil).
- In general excellent data-MC agreement



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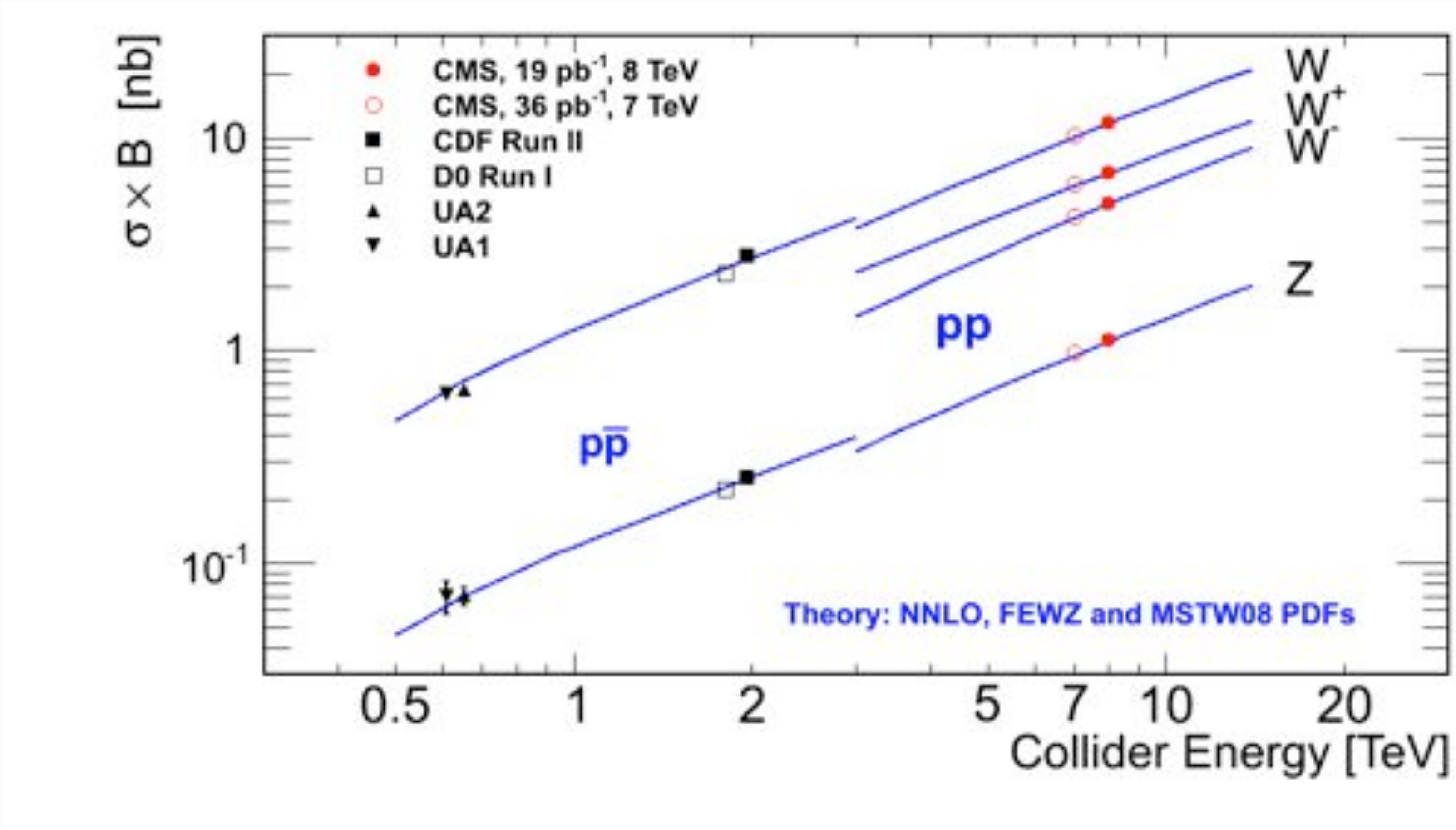
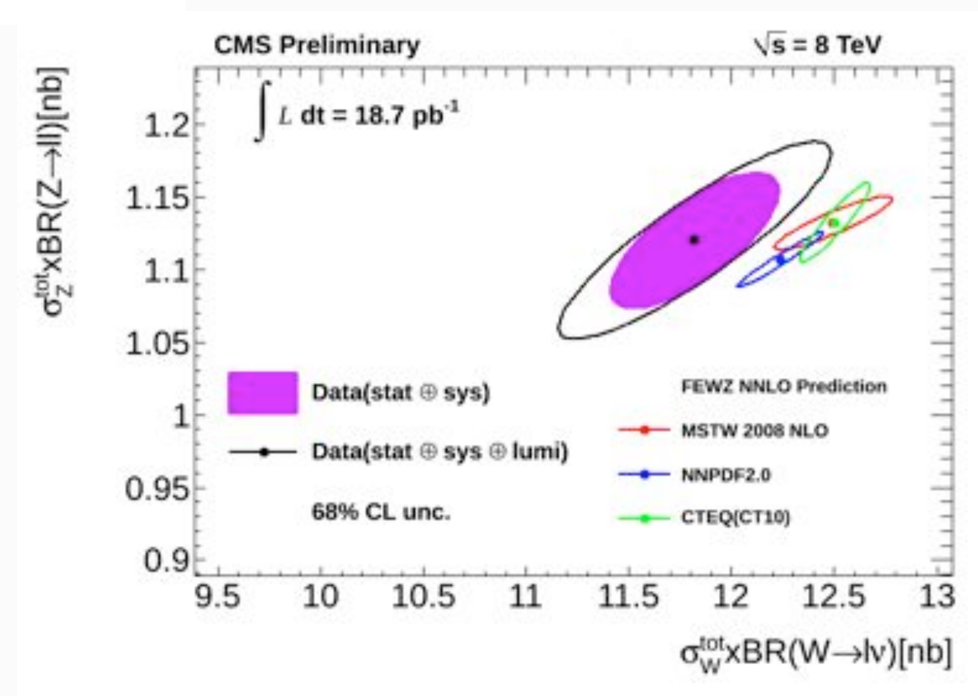
Amazing precision reached (~1% experimental !)
Start to put important constraints on theory (NNLO, PDFs)

Inclusive W and Z production

- Very recently: also first results at 8 TeV, using special low pile-up runs



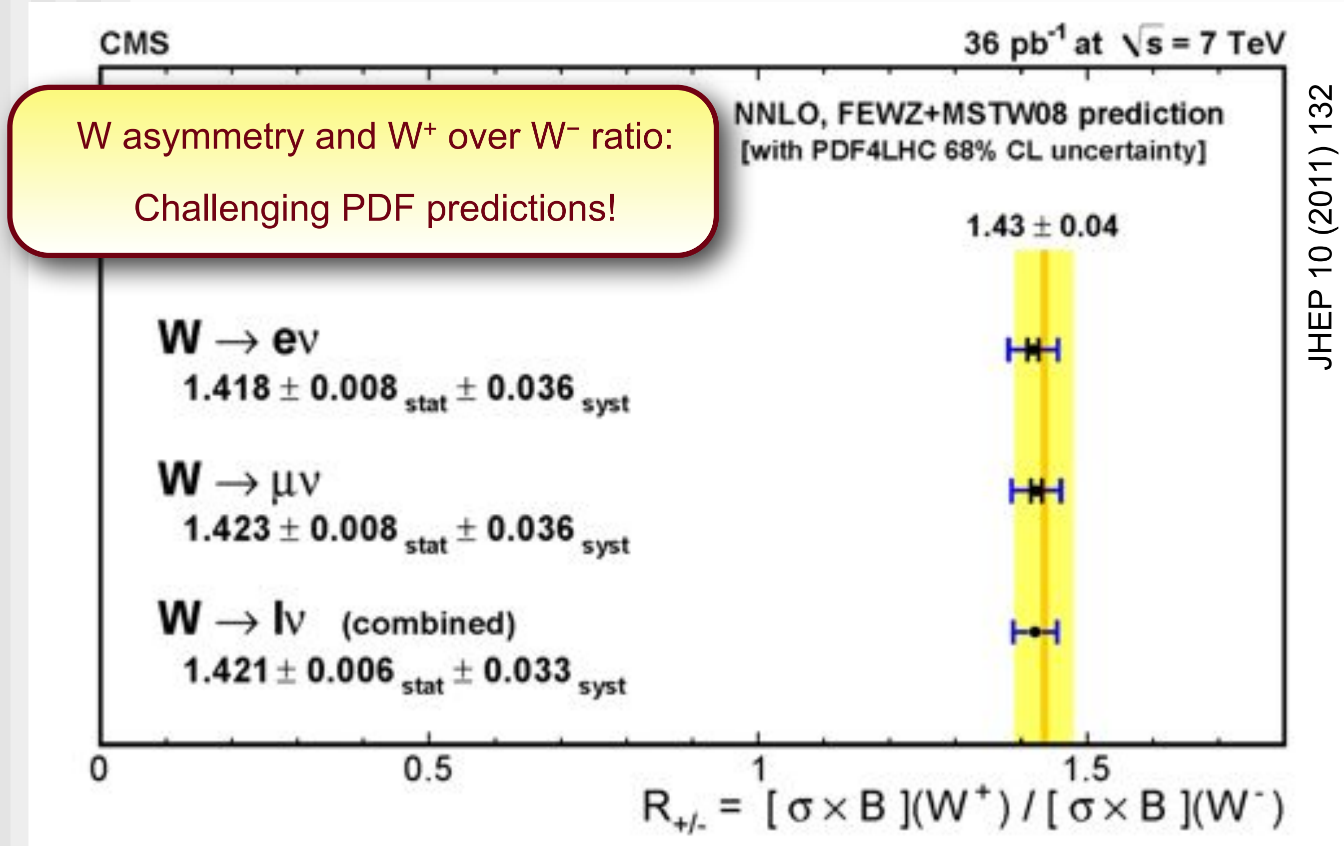
CMS PAS-SMP-12-011



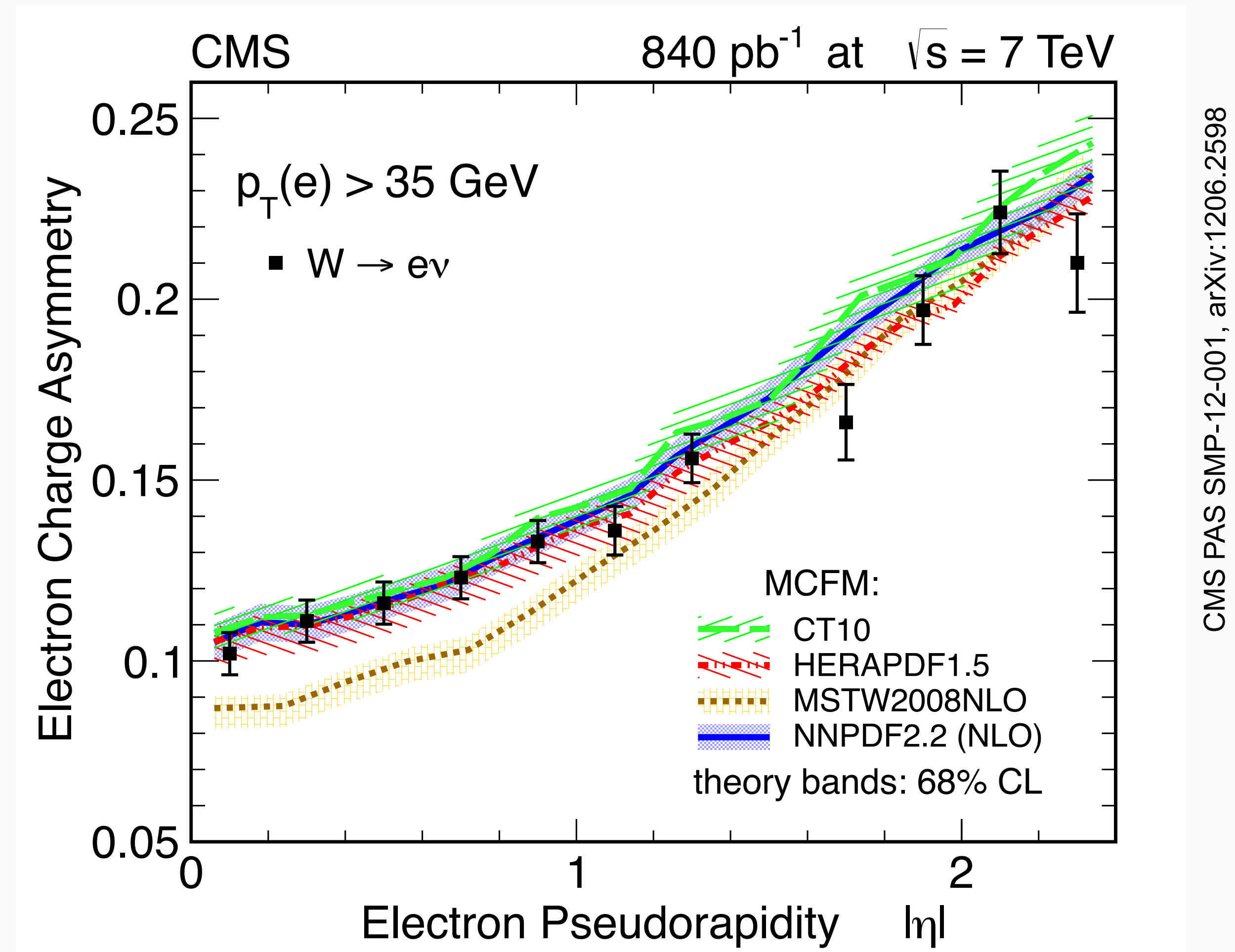
W properties, constraining PDFs

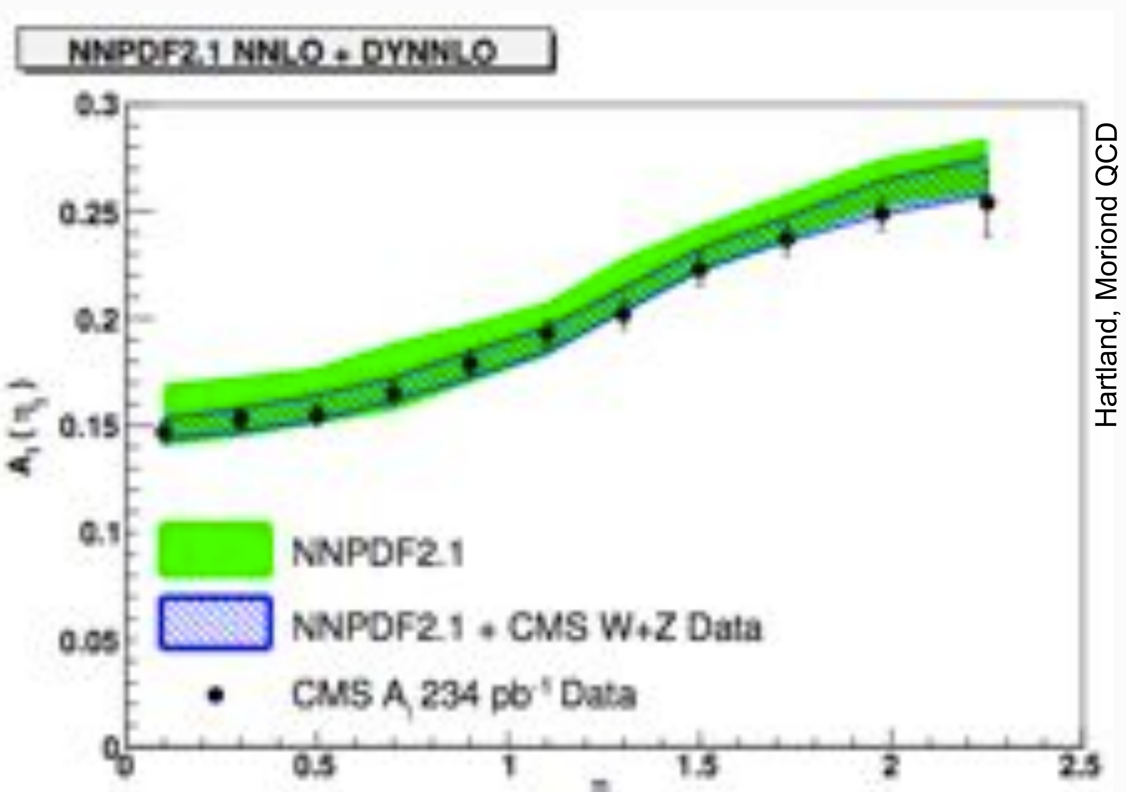
W asymmetry and W^+ over W^- ratio:

Challenging PDF predictions!



$$A(\eta) = \frac{d\sigma/d\eta(W^+ \to e^+\nu) - d\sigma/d\eta(W^- \to e^-\bar{\nu})}{d\sigma/d\eta(W^+ \to e^+\nu) + d\sigma/d\eta(W^- \to e^-\bar{\nu})}$$

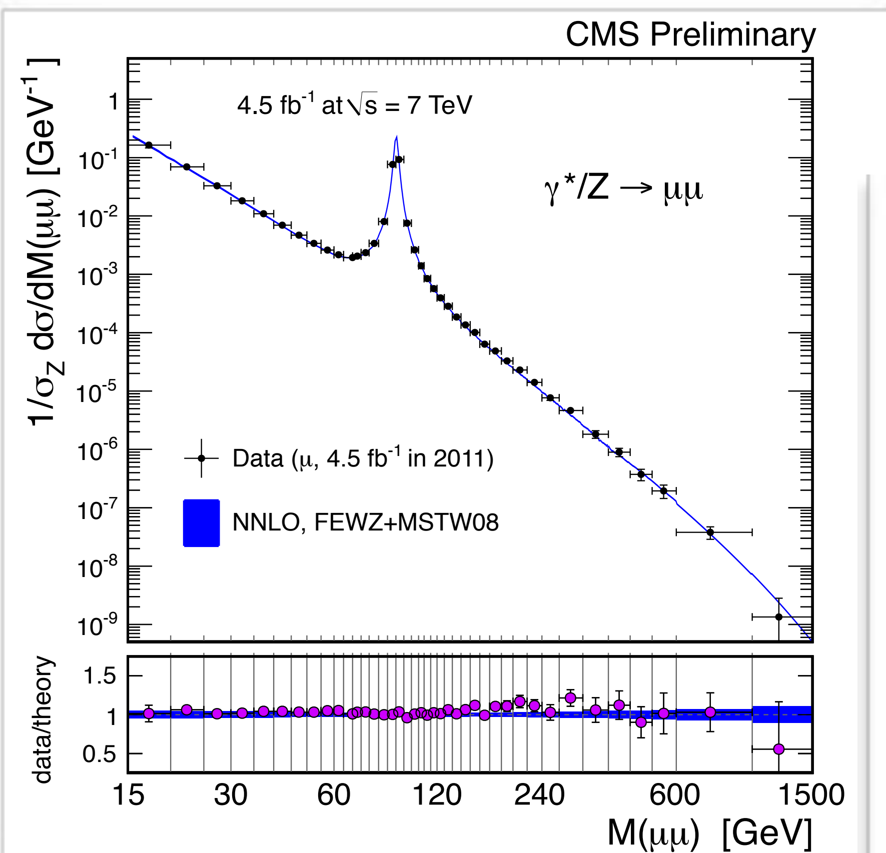




- **First results seen from NNPDF group when including such data**
- **looking forward to further global fits based on LHC data.....**

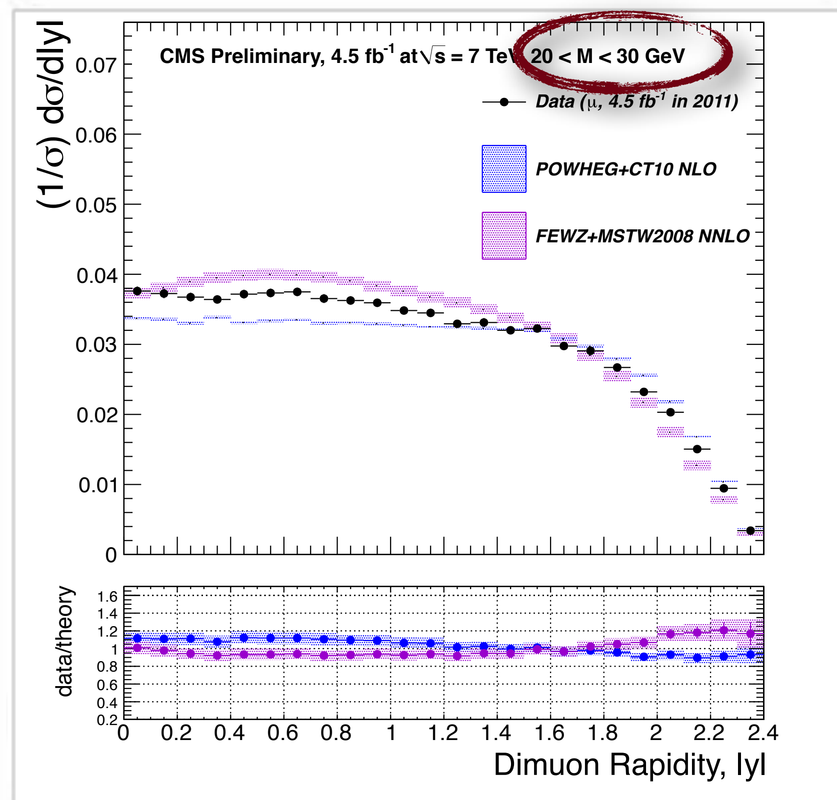
Many differential measurements...

di-lepton invariant mass (DY)

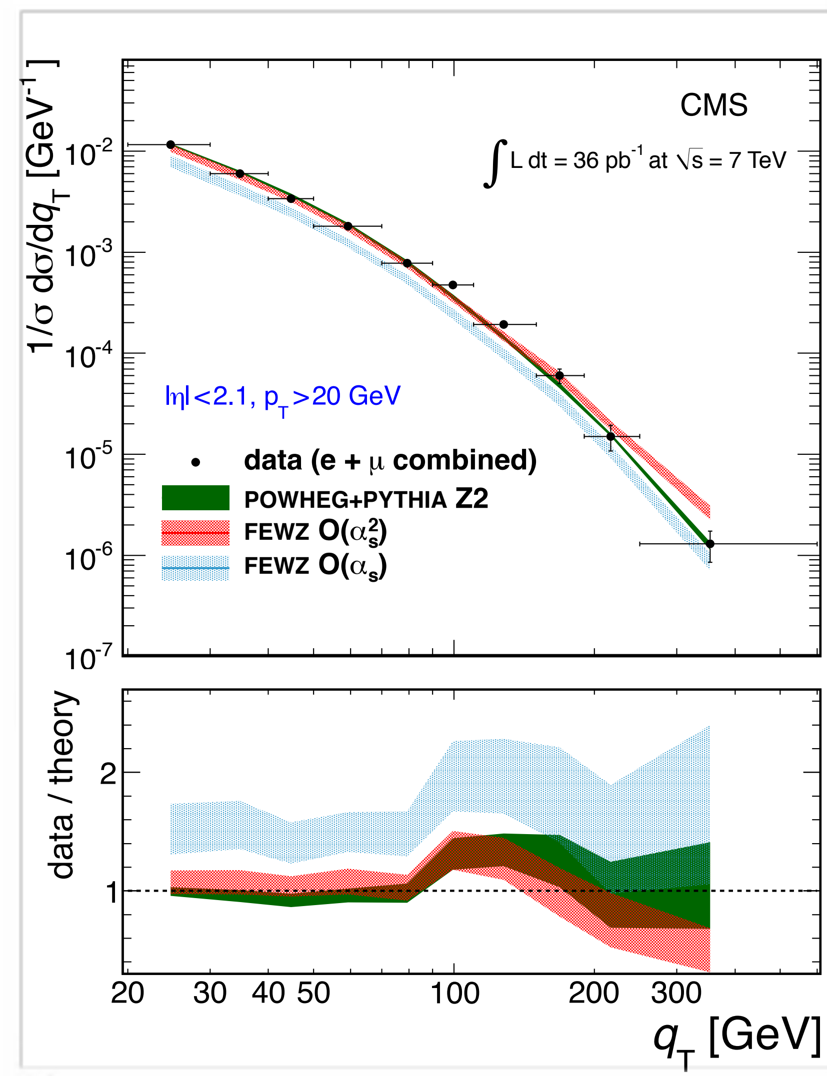


CMS-PAS-EWK-11-007

Di-muon rapidity



Z transverse momentum



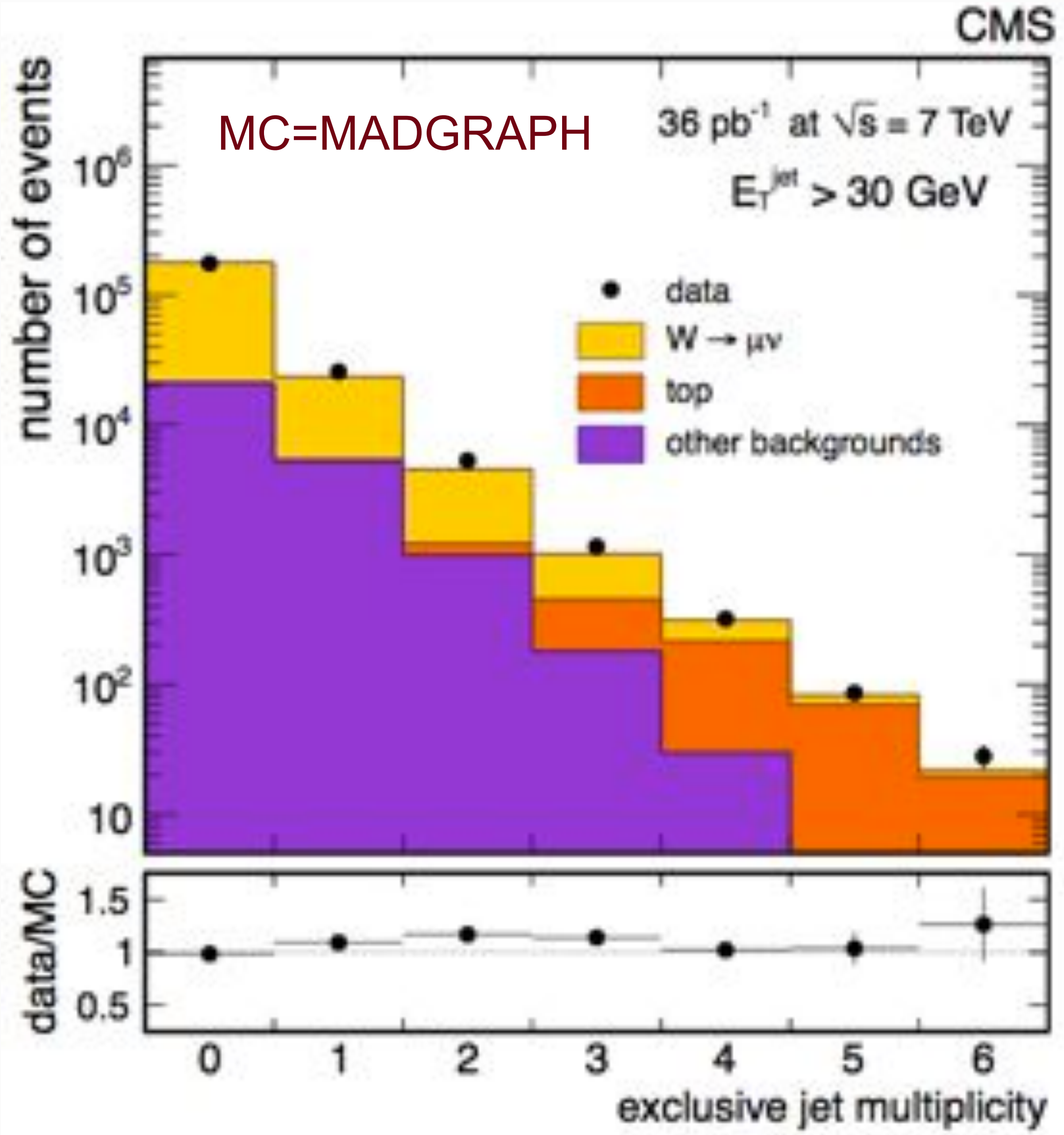
Phys. Rev. D 85 (2012) 032002

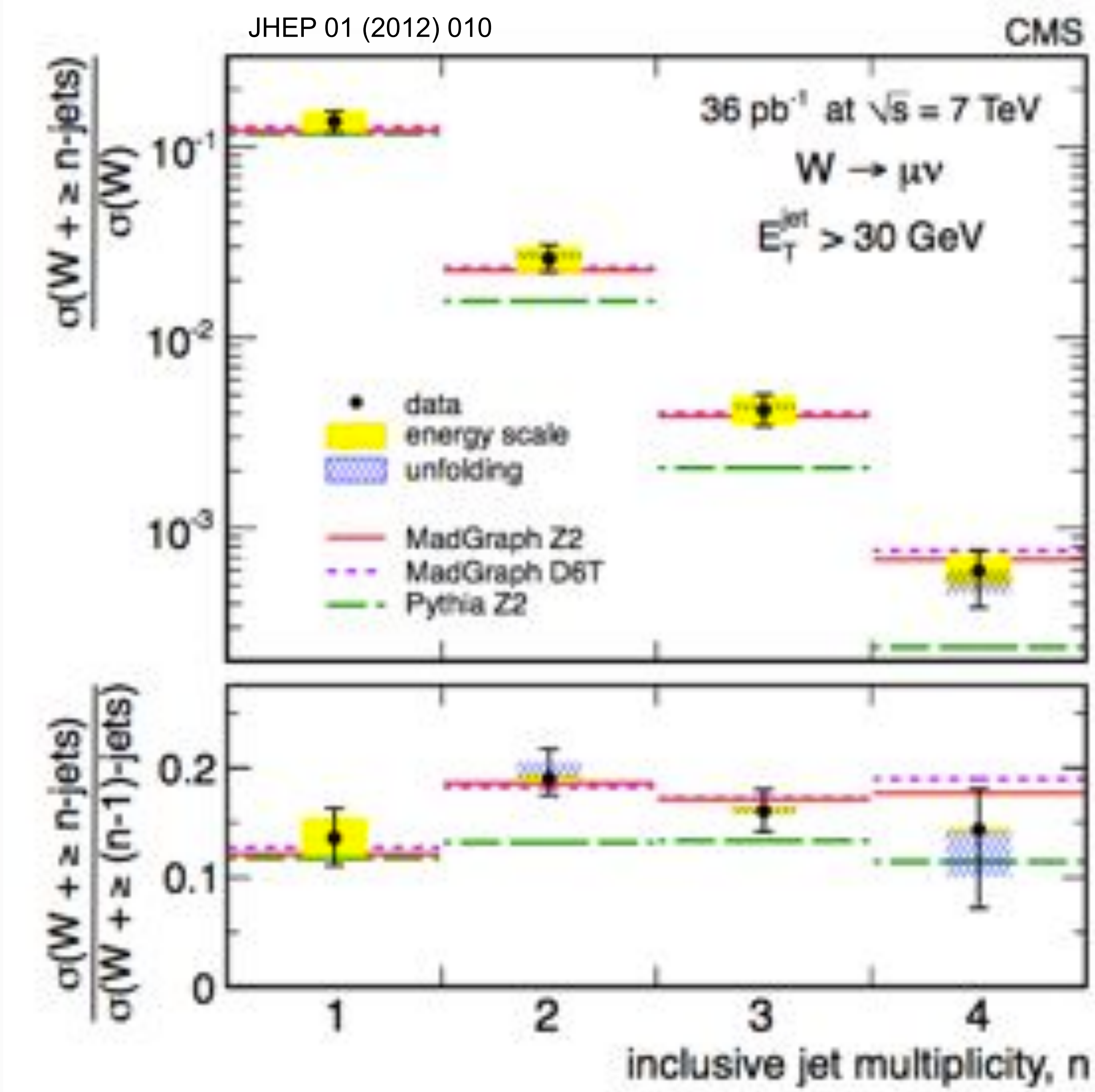
2.5M di-muon pairs, test of NNLO predictions and PDFs

good agreement seen at the Z peak

Vector Bosons + jets

ETH Institute for Particle Physics





- **important** processes for testing pQCD and backgrounds to very many searches!
- **in CMS, for W+jets: simultaneous** extraction of W signal and top background
- final distributions: **unfolded to particle level**
- presented for experimental lepton and jet acceptance, eg. p_{Tjet} > 30 GeV

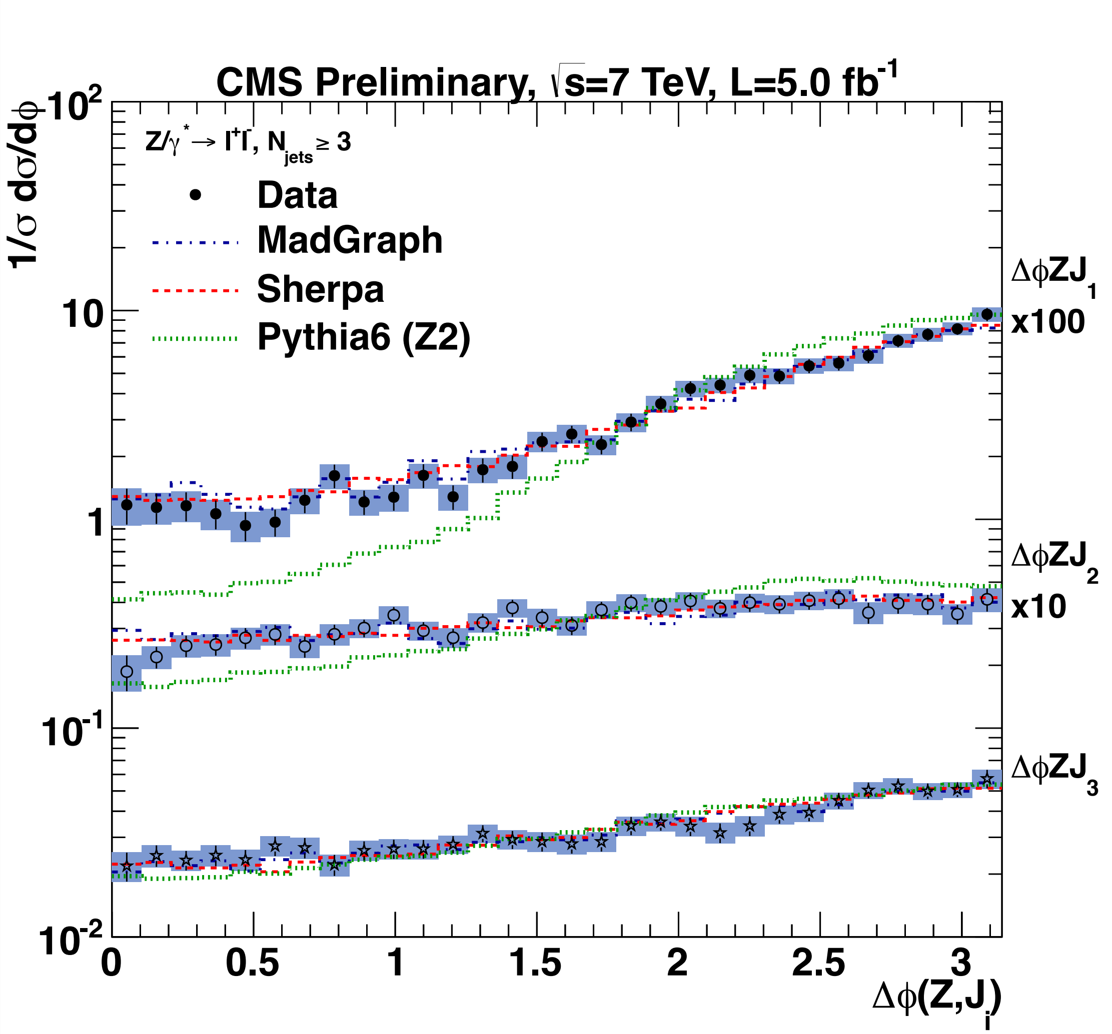
An additional jets "costs" ~1 $alpha_s$

Excellent agreement with ME+PS matched Monte Carlo model.

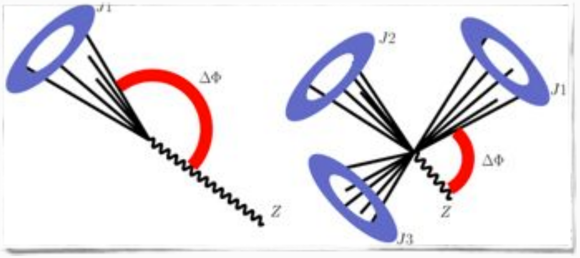
Z+jets: more differential

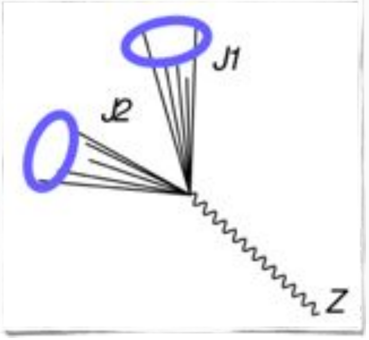
CMS-PAS-EWK-11-021

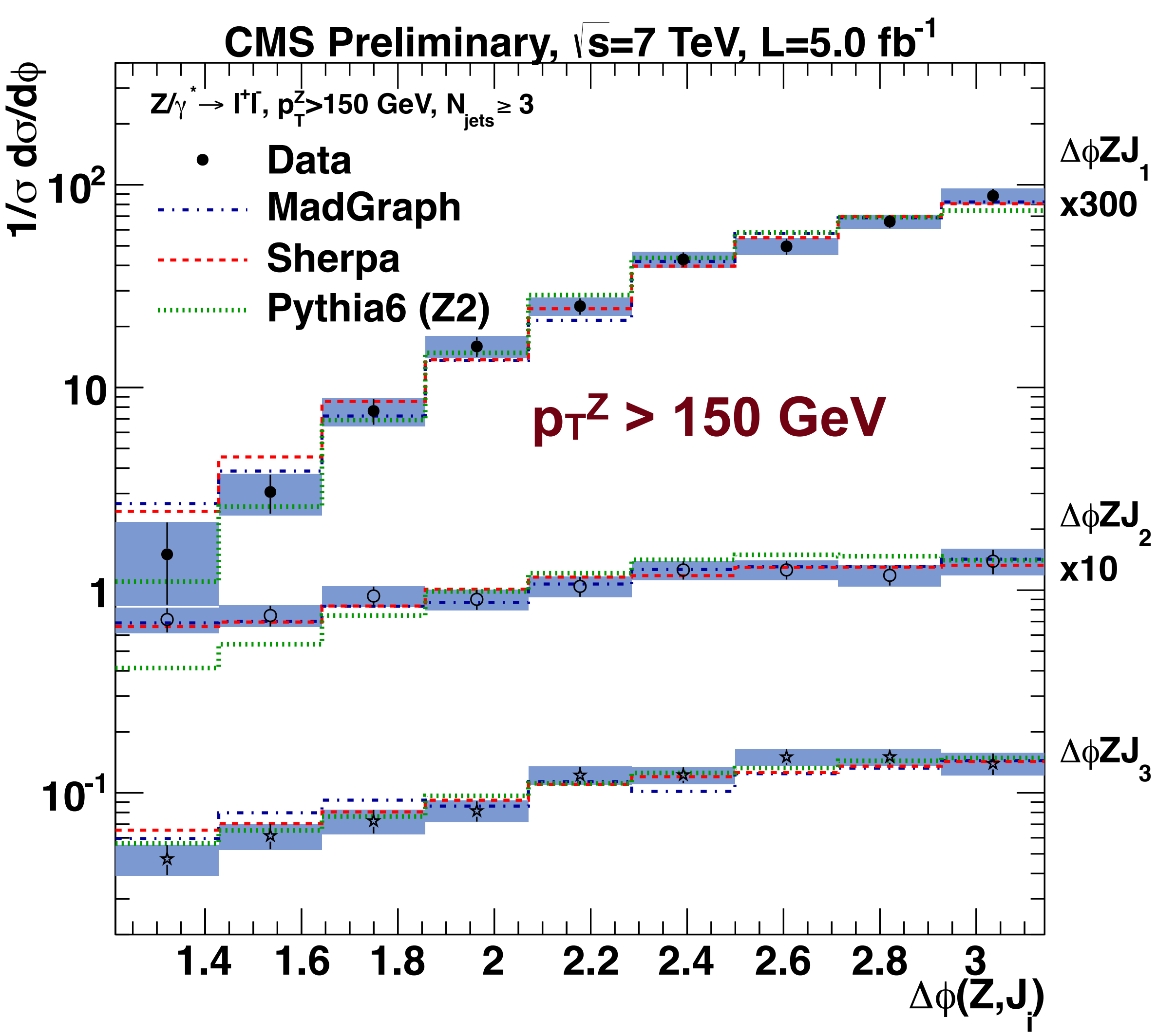
- **New:** high-stat. measurements of Z+jets production, in particular testing angular correlations and event shapes,
- for different regions of phase space (in p_T^Z) : useful for testing phase space relevant for searches



- Jet reconstruction:
  - anti-kt with radius of 0.5 and pT>50 GeV



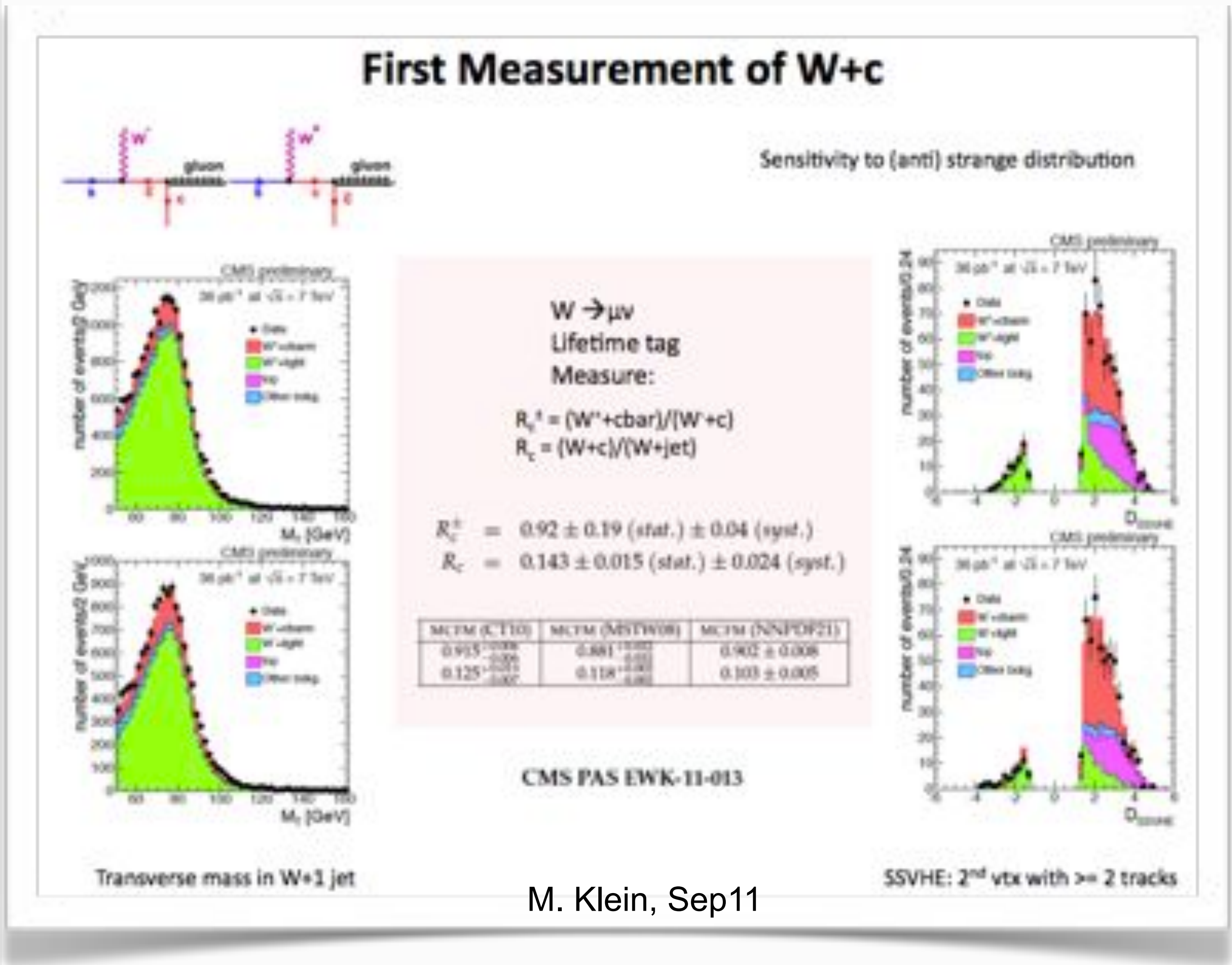




Again: a success for ME+PS matched Monte Carlo models!

Note: for subleading jets and boosted regime a simple PS does pretty well

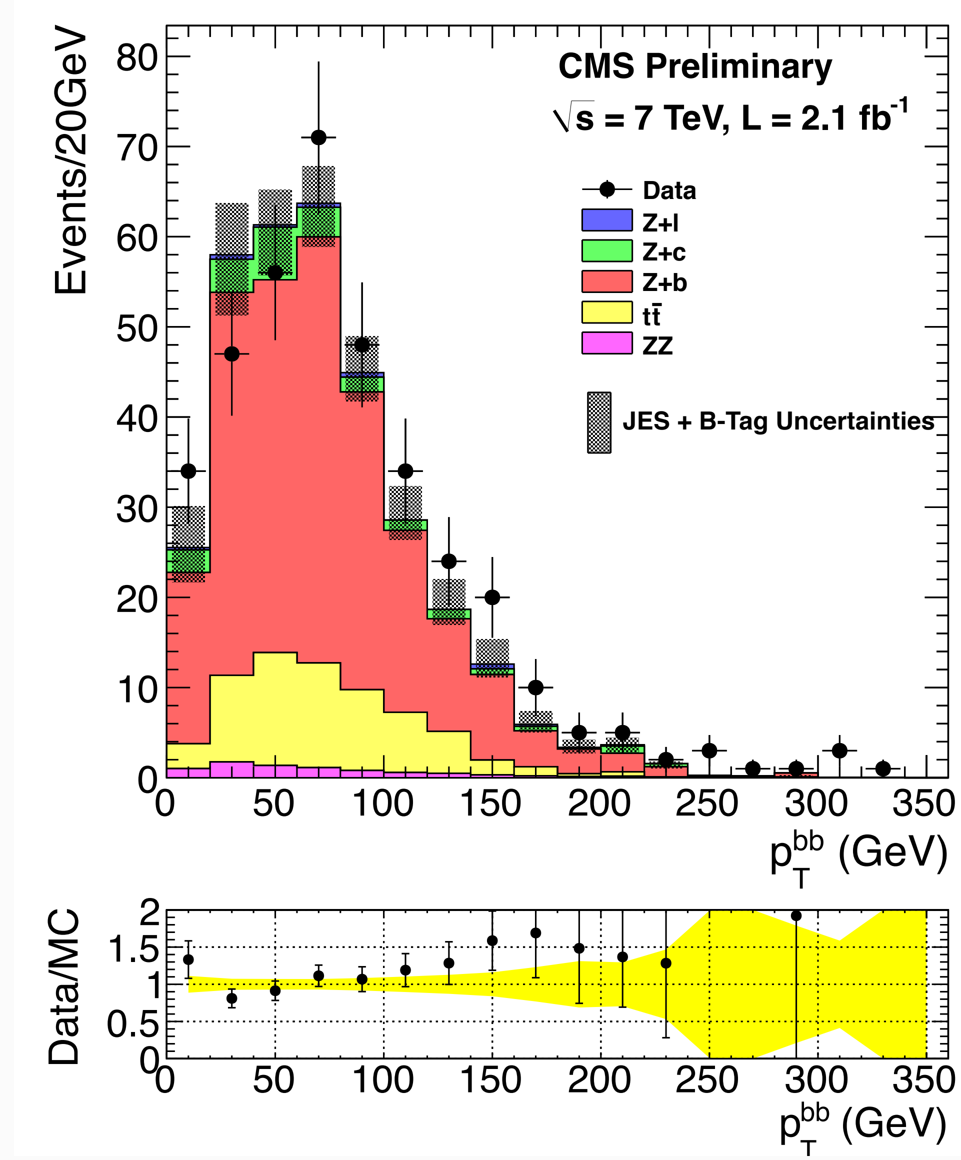
V plus heavy flavour



M. Klein, Sep11

Z+ bb-jets prod.

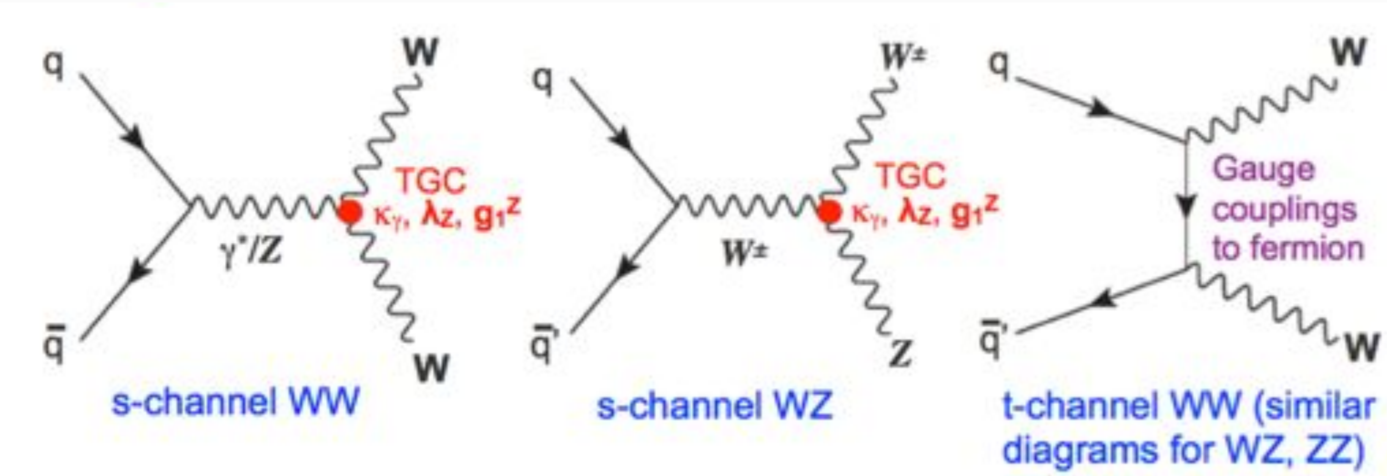
CMS-PAS-SMP-12-003



W+c and Z+b most relevant to constrain PDFs, relevant for later high-precision W mass measurement.

So far, no major discrepancies seen compared to NLO (in contrast to W+b prod....)

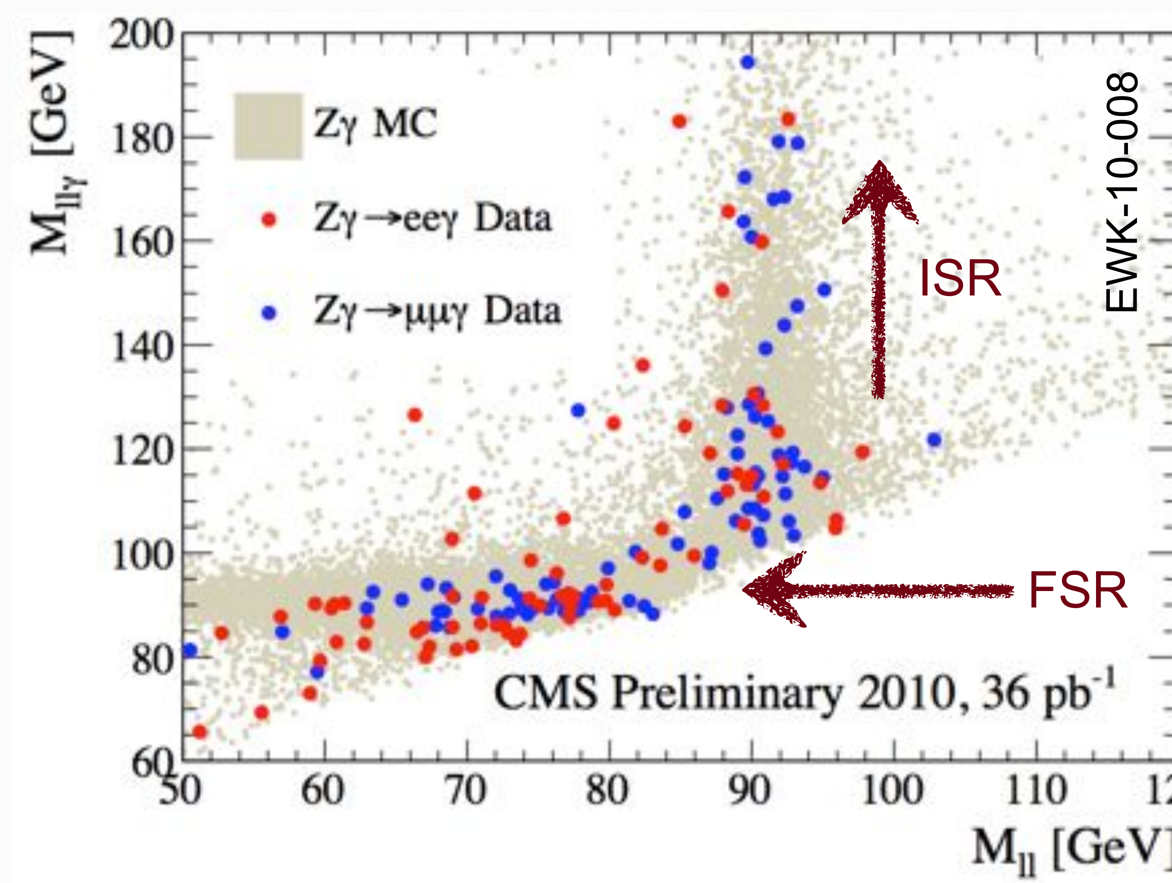
Di-Boson Production



- **Critical test of the gauge structure of the SM**
  - Allows to search for anomalous Triple Gauge Couplings (TGC)
- **Mandatory preliminary study for Higgs searches**: irreducible background for Higgs searches in WW and ZZ modes
- Probe for new physics
  - Resonances with diboson final states

- **WW and ZZ:** see next slide

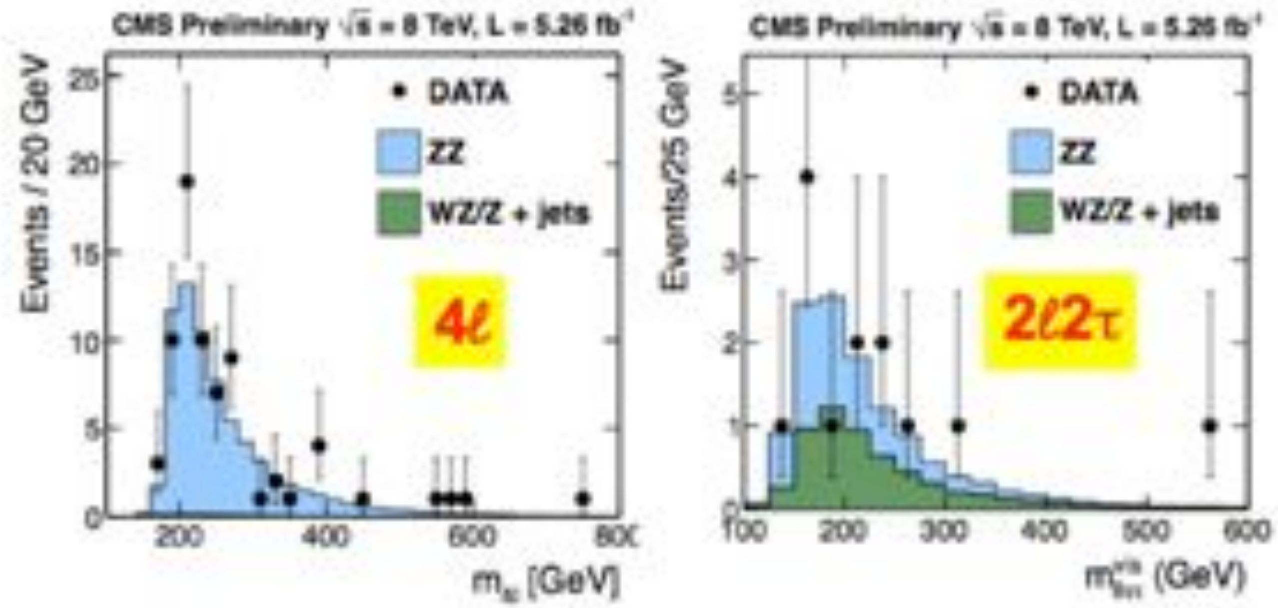
- **Wγ and Zγ**
  - cross sections measured for $E_{T\gamma}$> 10 GeV and dR(lept,γ)> 0.7
  - cross sections in agreement with SM predictions
  - first limits on WWγ,ZZγ,Zγγ TGC at 7 TeV



WW and ZZ production

slide adapted from P. Meridiani

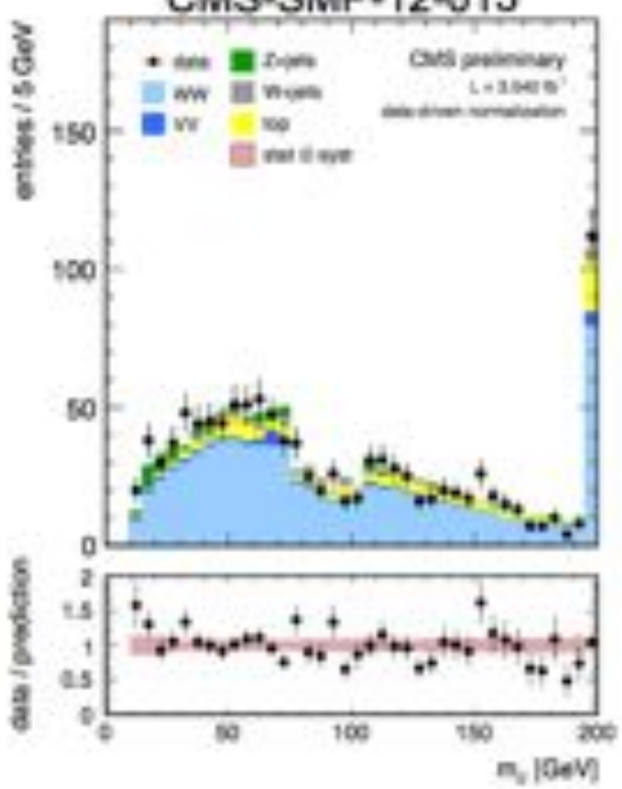
CMS-SMP-12-014



ZZ

$\sigma = 8.4 \pm 1.0\ (\text{stat}) \pm 0.7\ (\text{sys}) \pm 0.4\ (\text{lum})$ pb
NLO (MCFM 6.0): 7.7 ± 0.4 pb
(NLO for $qq \to ZZ$ and LO for $gg \to ZZ$, MSTW 2008 PDF)

CMS-SMP-12-013



WW: 2 opposite sign leptons (e,μ) + MET + jet veto
All backgrounds are estimated from data

$\sigma = 69.9 \pm 2.8\ (\text{stat}) \pm 5.6\ (\text{sys}) \pm 3.1\ (\text{lum})$ pb

NLO prediction:
$\sigma^{NLO}(gg \to W^+W^- + qq \to W^+W^-) = 57.25\ (^{+2.35}_{-1.60})$ pb

Campbell, Ellis, Williams. JHEP 07 (2011), 018. arXiv:1105.0020, MCFM

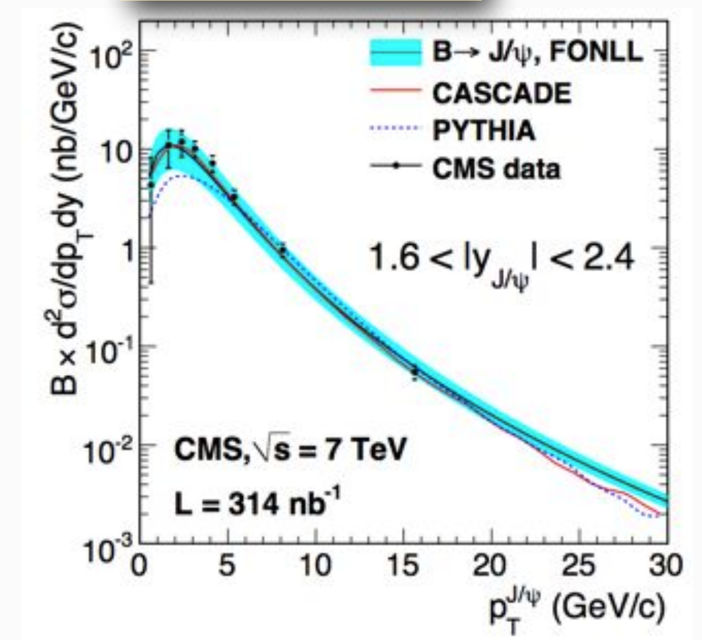
Also at 7 TeV seen: slightly larger WW xsec measured than predicted by NLO QCD

Something interesting there? To be followed up....

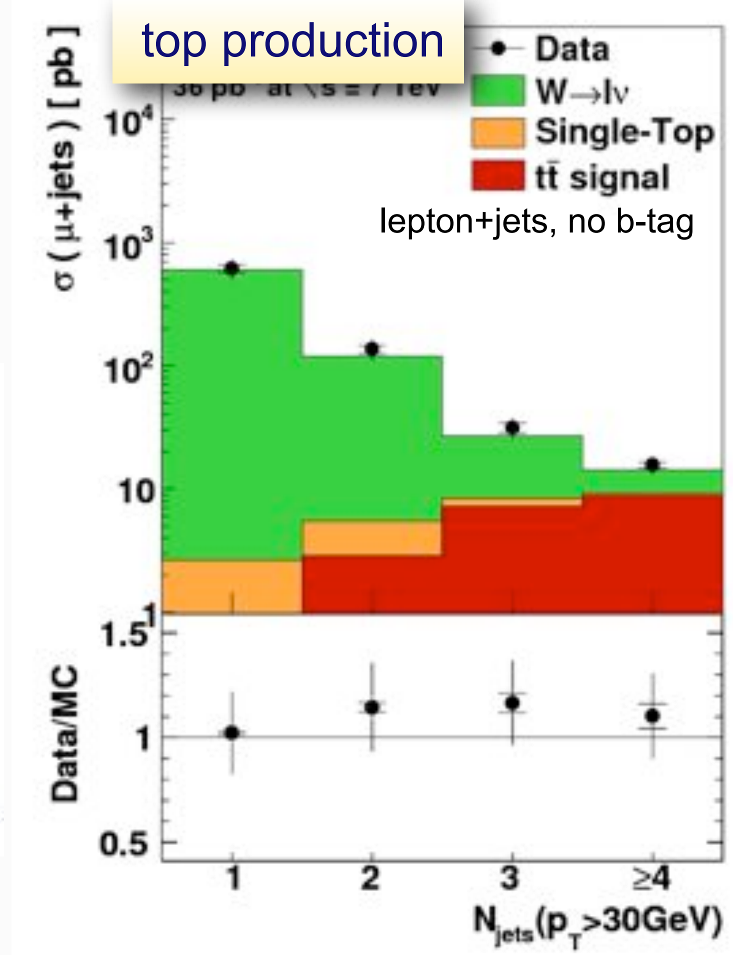
Production of "heavy" quarks:

s → c (Quarkonia) → b → top

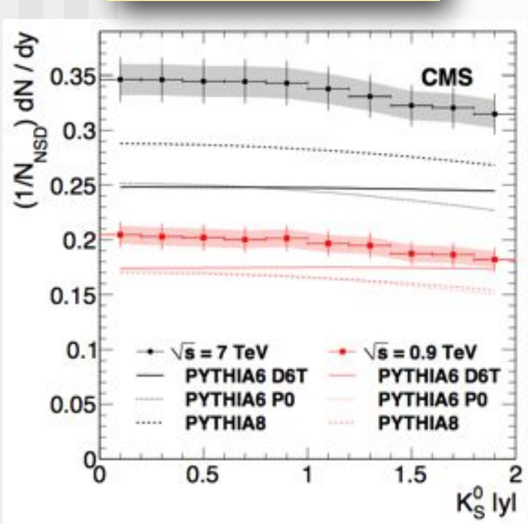
J/Ψ production



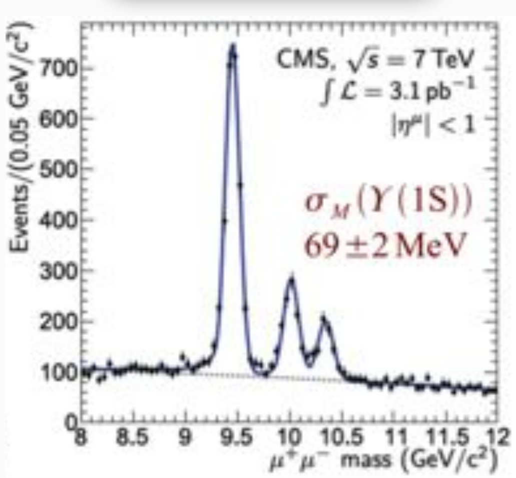
top production



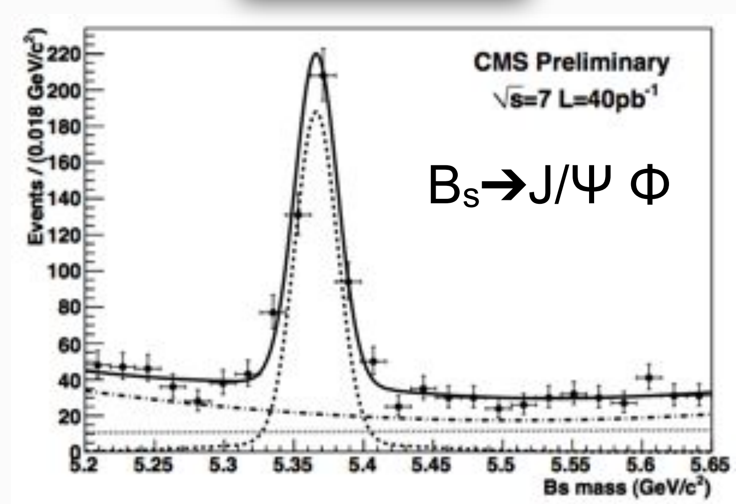
Ks production



Y production



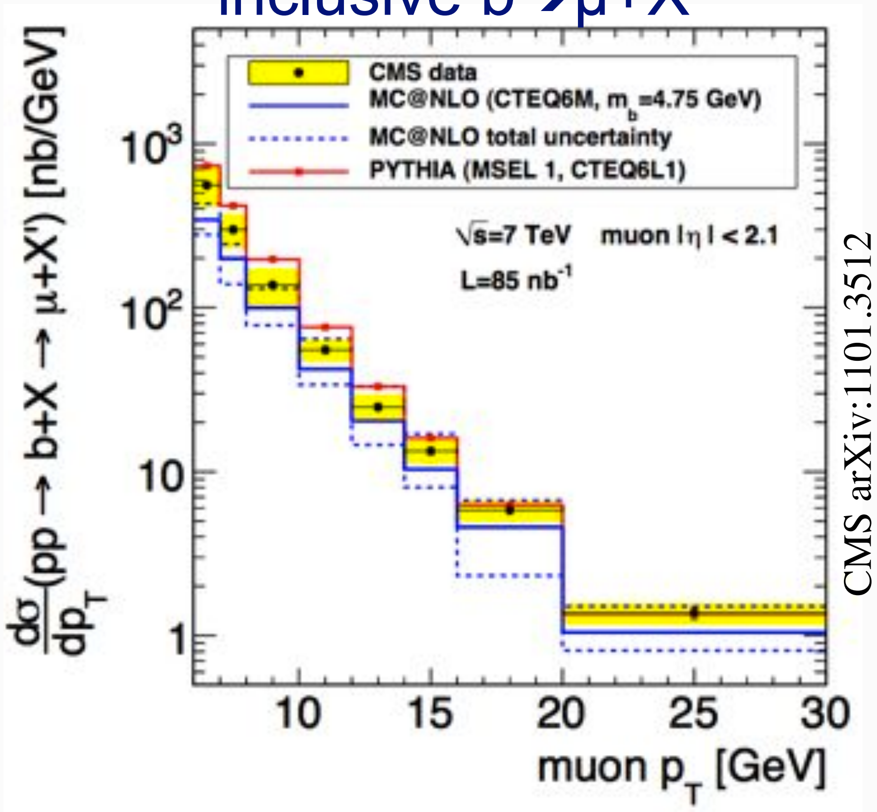
excl. states



B_s → J/Ψ Φ

b/B : differential cross sections

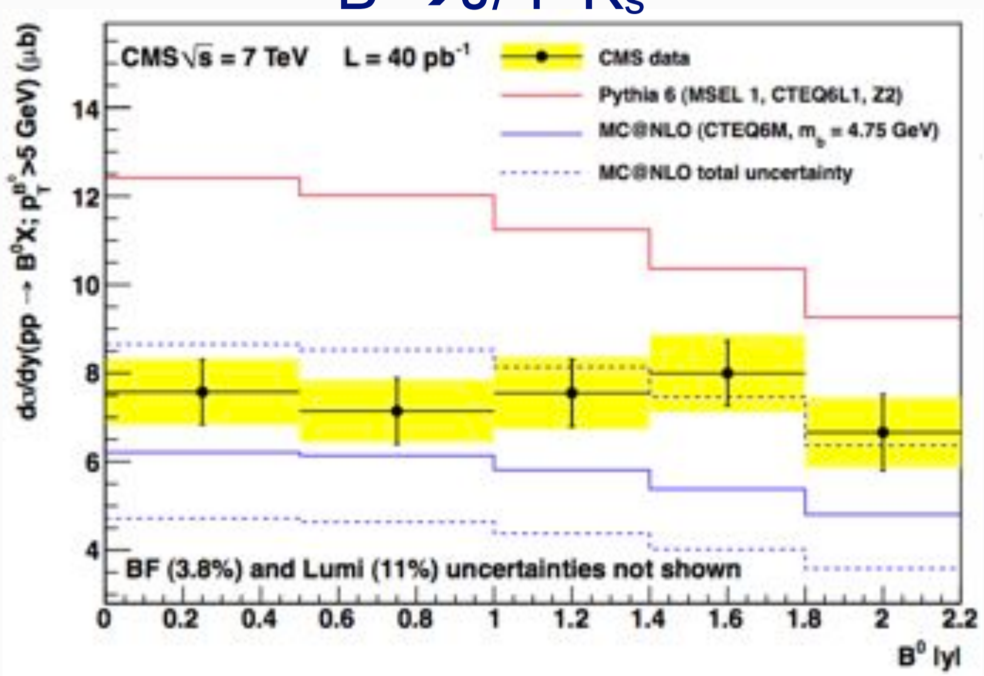
inclusive b→μ+X



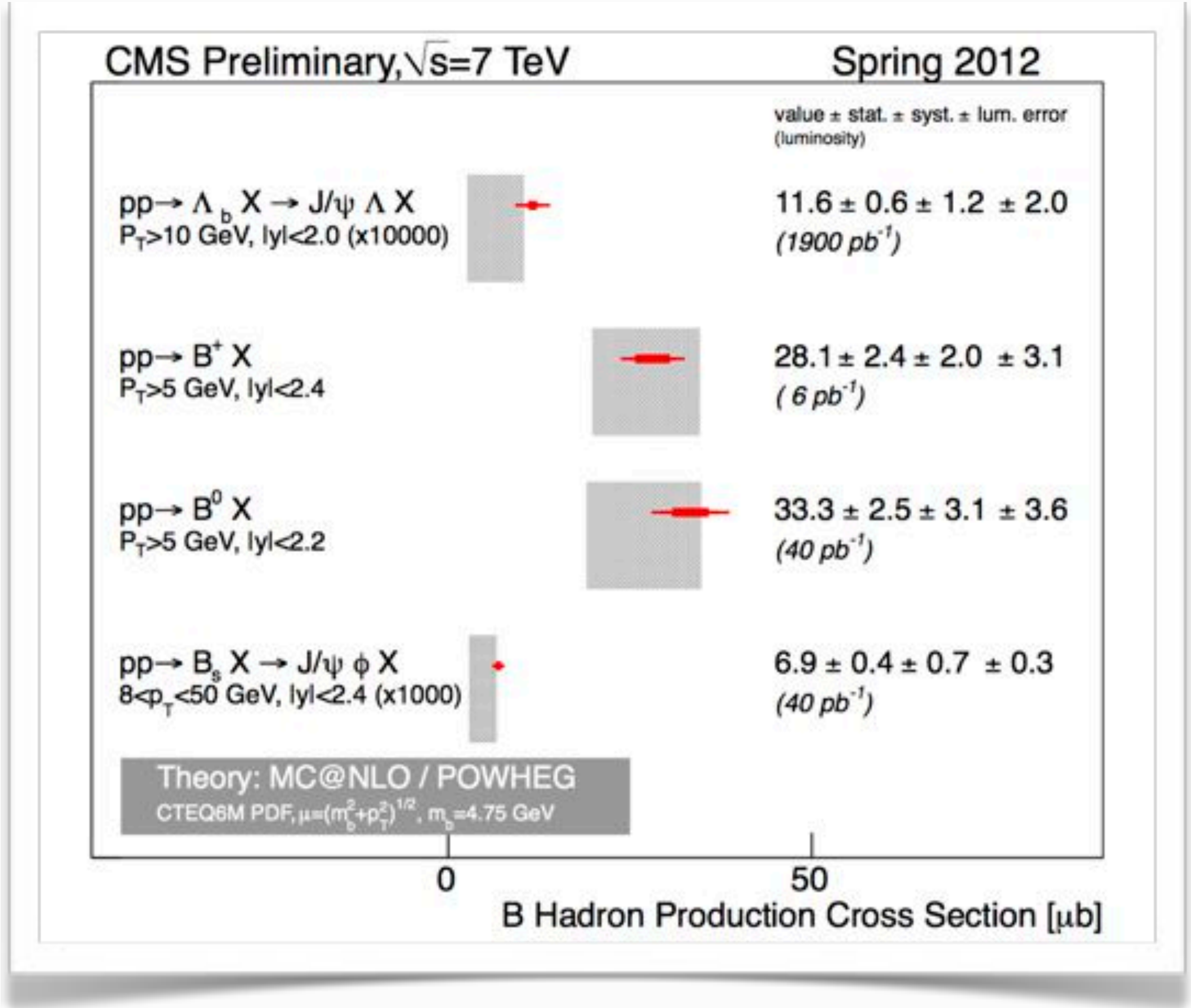
CMS arXiv:1101.3512

Extensive studies of b/B production. Consistent picture in all channels:
Data between predictions of MC@NLO and Pythia;
differences in shape, both for p_T and rapidity distributions.

B^0→J/Ψ K_s

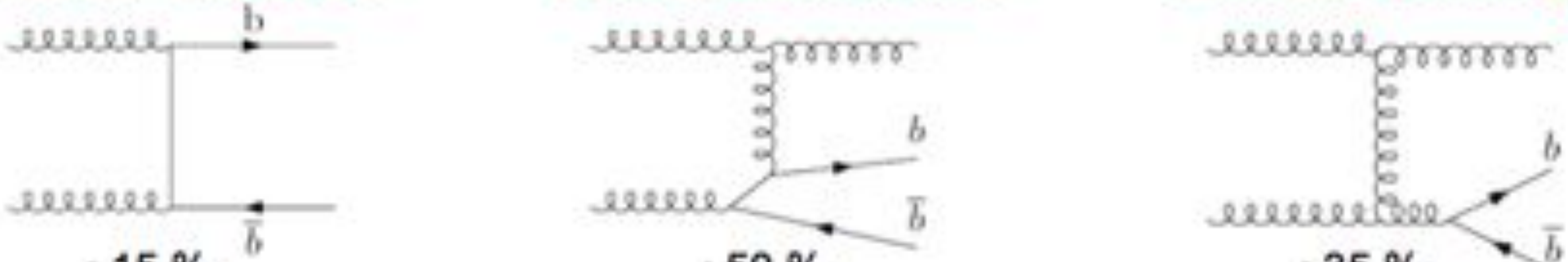


CMS PAS BPH-10-005

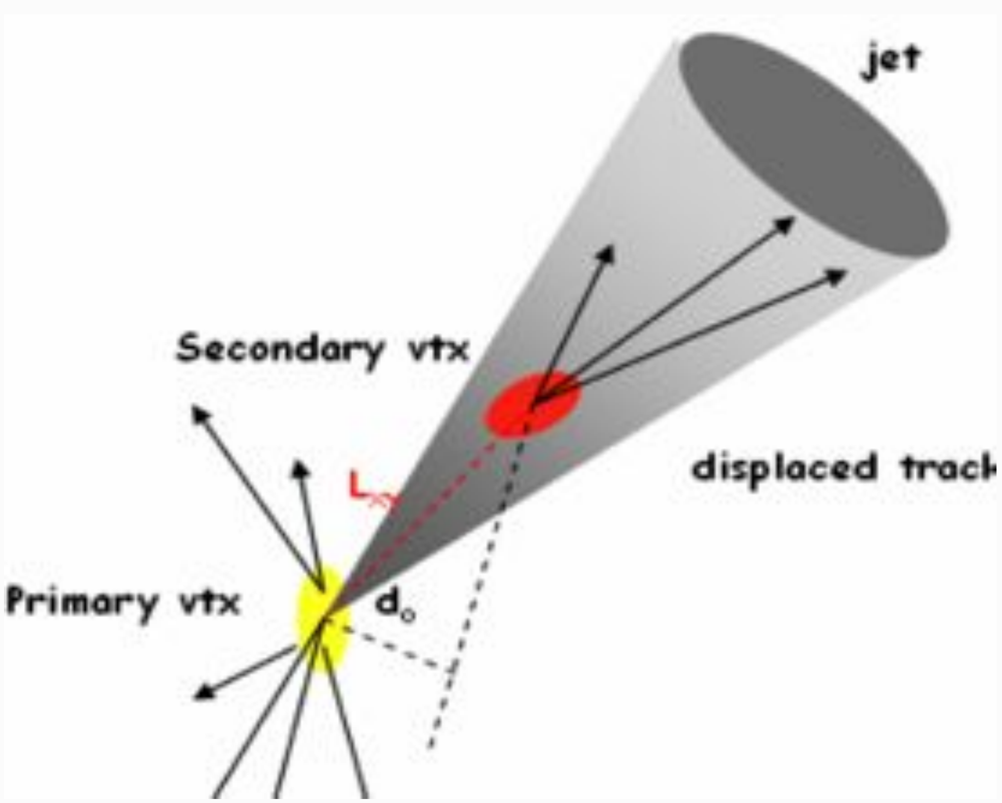


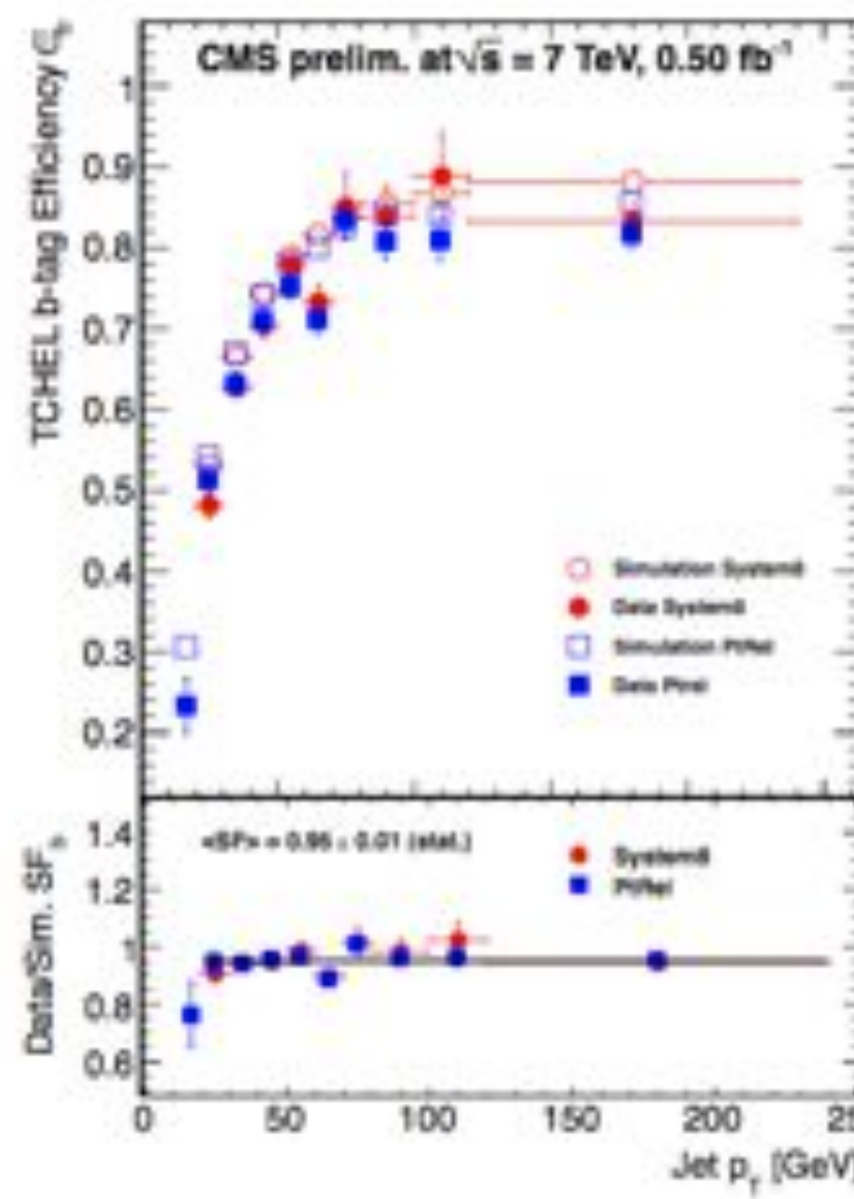
b-jet production

Flavor Creation	Flavor Excitation	Gluon Splitting	
~15 %	~50 %	~35 %	for p_T 20-100 GeV



- FEX, GS are higher order effects but dominate at LHC





b-tagging:
Secondary vertices, impact parameter, muons from heavy flavour decays

b-jet production: Results

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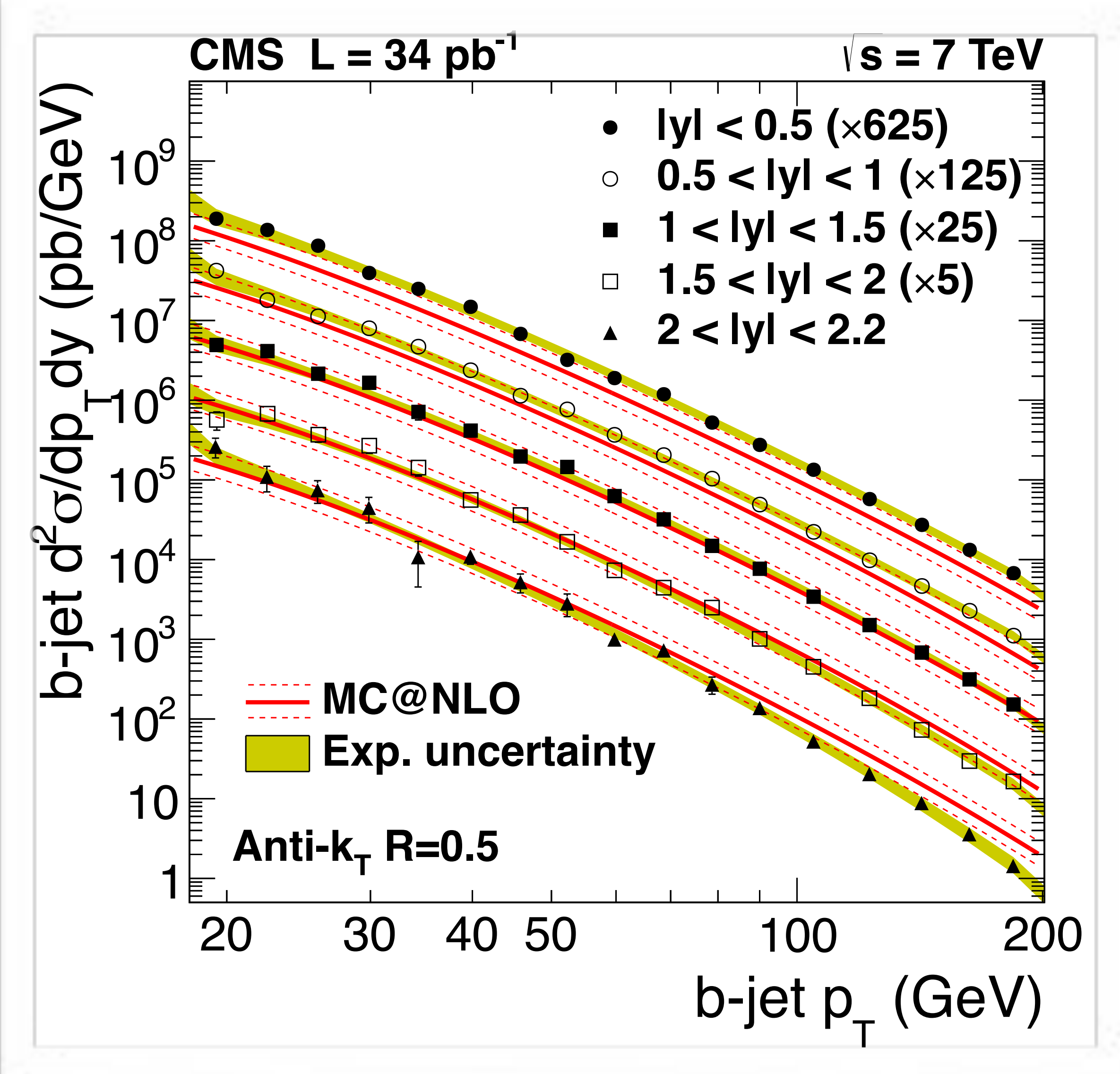
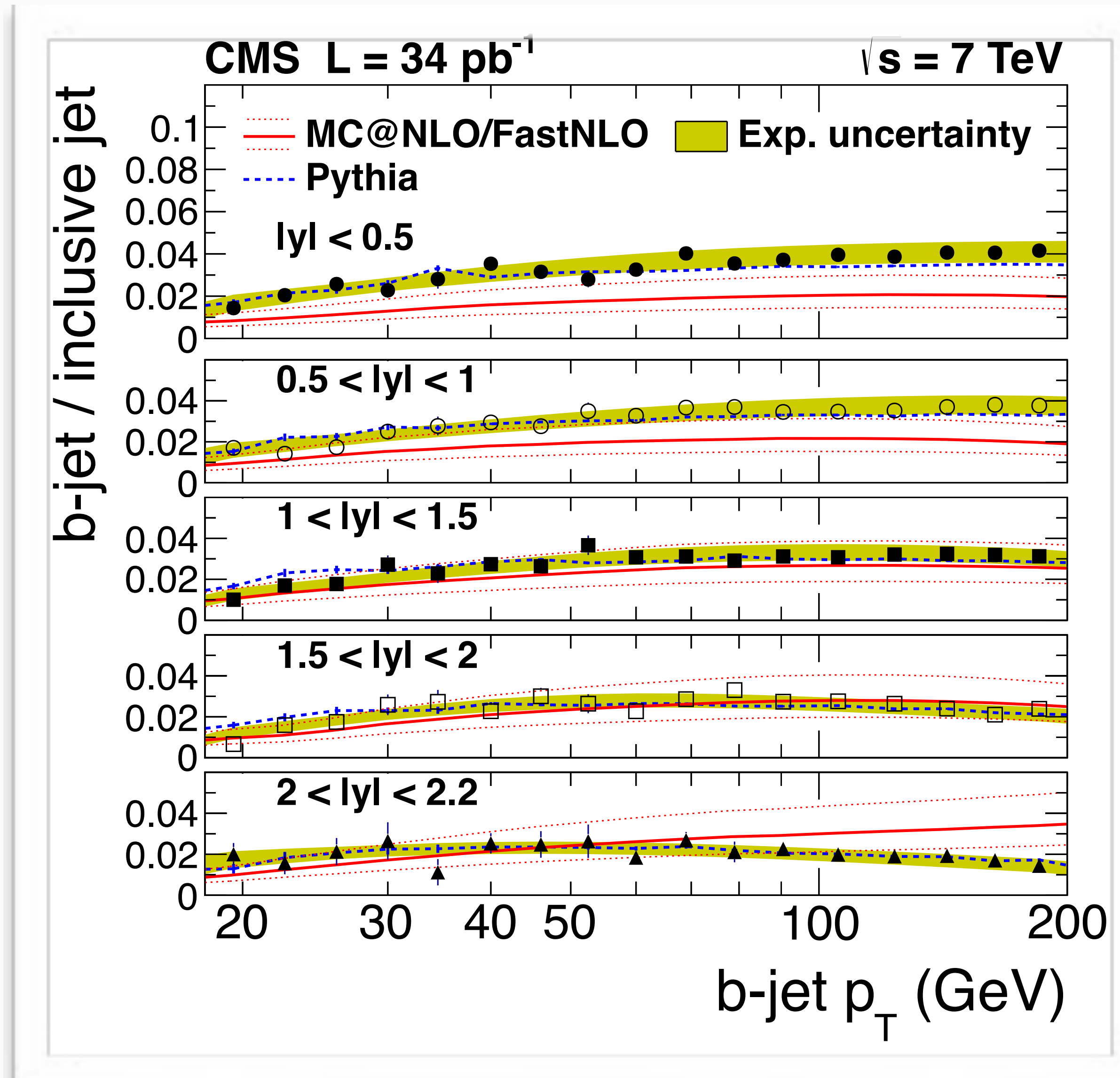
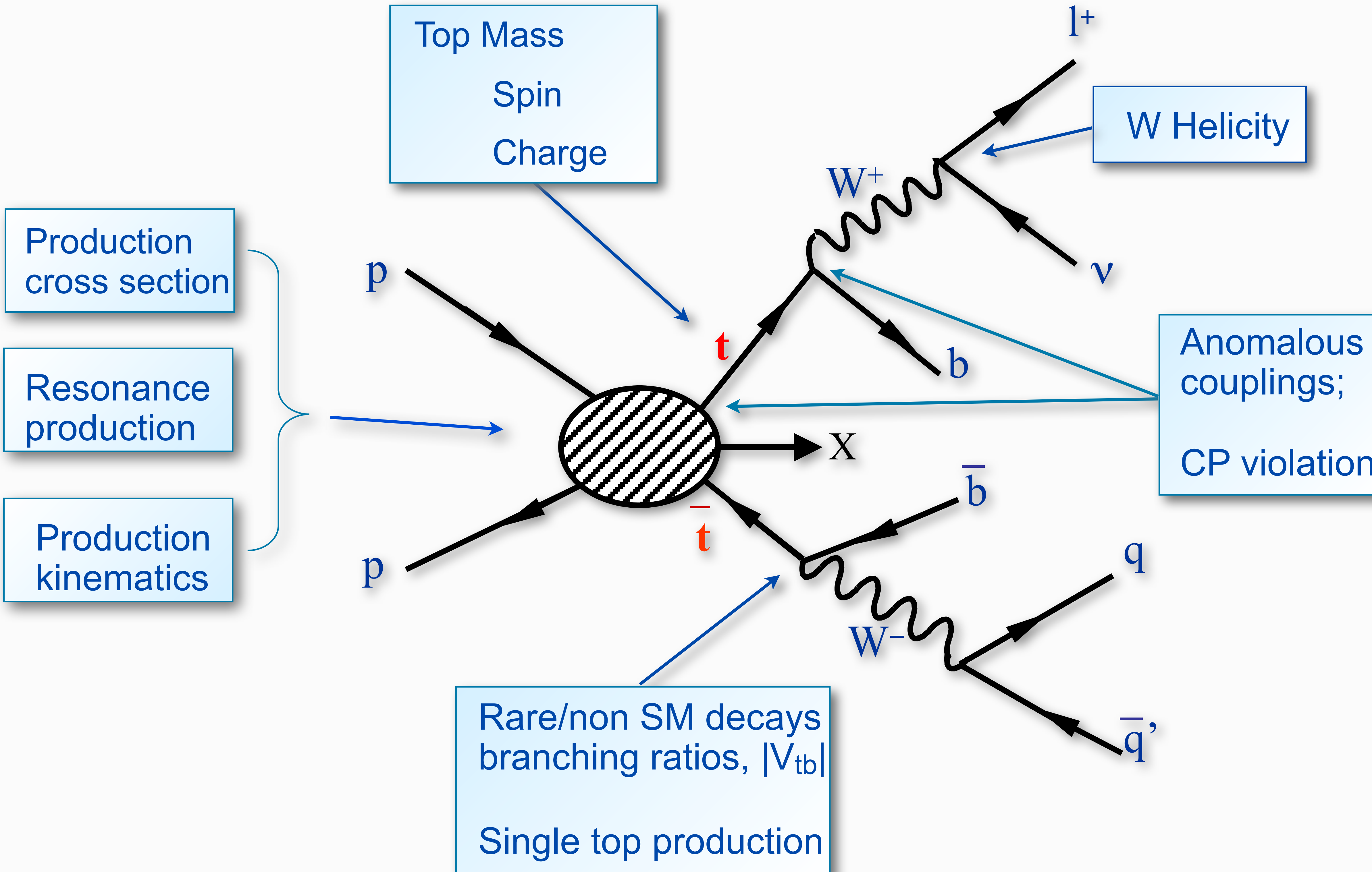


JHEP 04 (2012) 084



- Some discrepancies seen with MC@NLO
- ratio to inclusive jet cross section helps to eliminate some systematics (eg. lumi)
- this ratio better described by Pythia, in particular for forward jets!

Top Quark Physics



Everybody says: "... the top quark is special!"

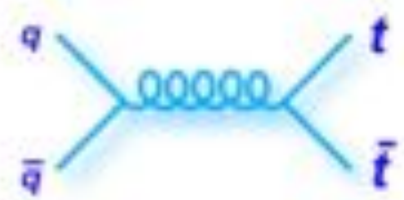
By now, all the other quarks must suffer psychological damage

Top Production

slide adapted from FP. Schilling

Gluon fusion (dominant at LHC)

Quark-antiquark annihilation

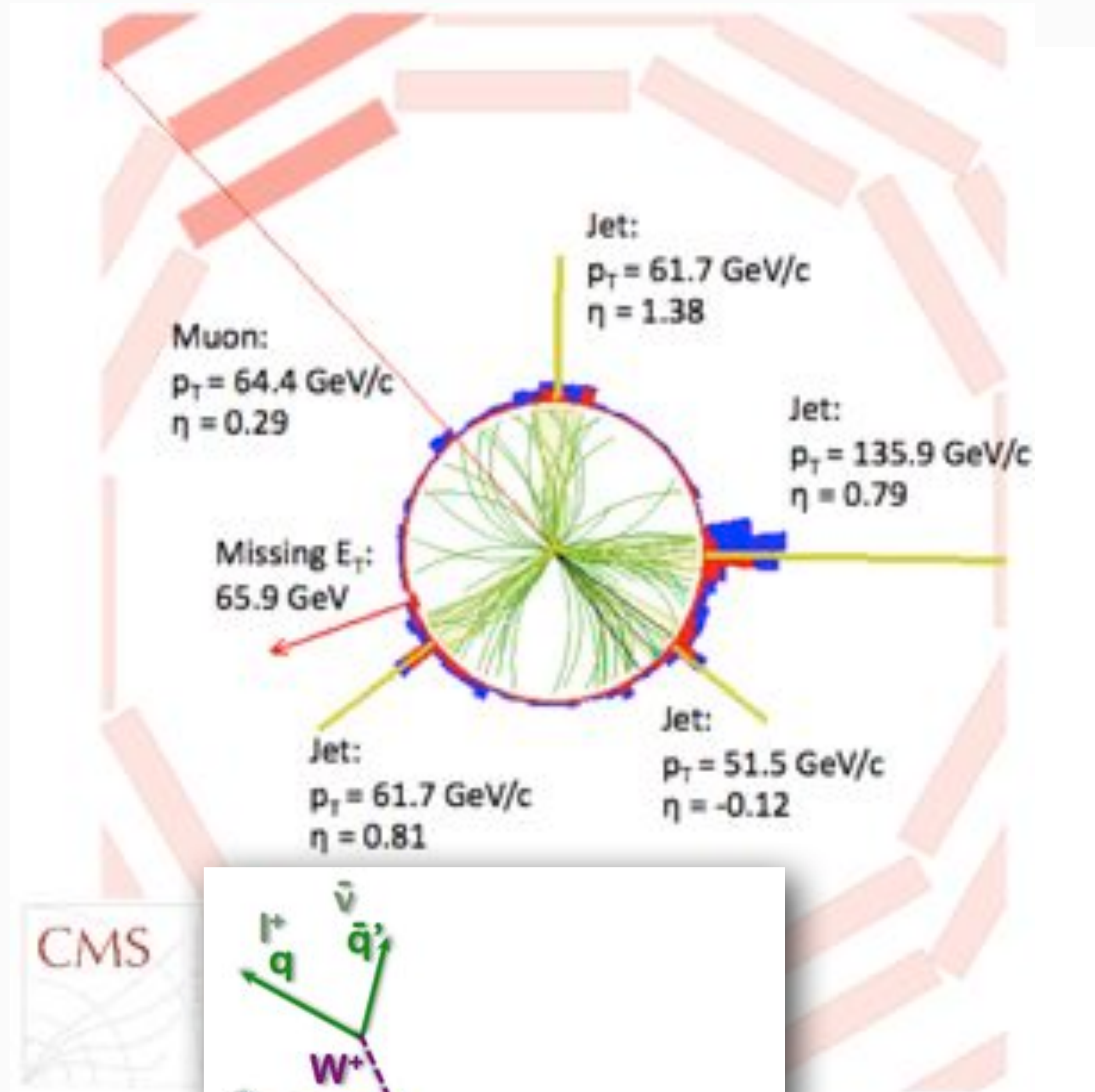


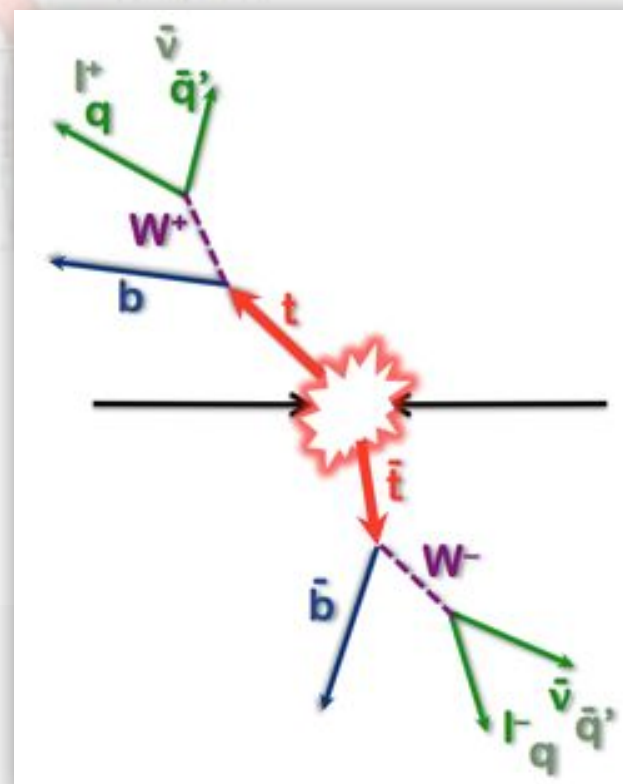
Total cross section at 7 TeV:

- NLO (MCFM) $\sigma_{t\bar{t}}^{\mathrm{NLO}} = 158^{+23}_{-24}\ \mathrm{pb}$
- approx. NNLO
  - Kidonakis, PRD 82 (2010) 114030

    $\sigma_{t\bar{t}} = 163^{+11}_{-10}\ \mathrm{pb}$
  - Langenfeld, Moch, Uwer, PRD80 (2009) 054009
  - Aliev et al., CPC182 (2011) 1034

    $\sigma_{t\bar{t}} = 164^{+10}_{-13}\ \mathrm{pb}$

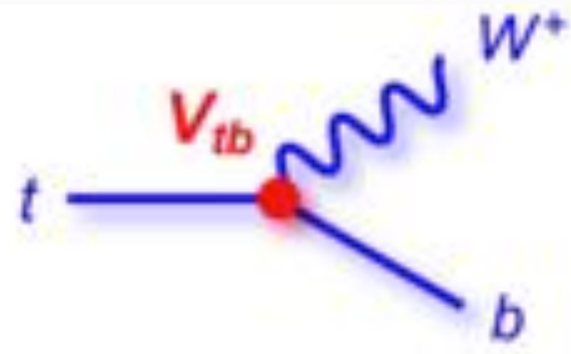




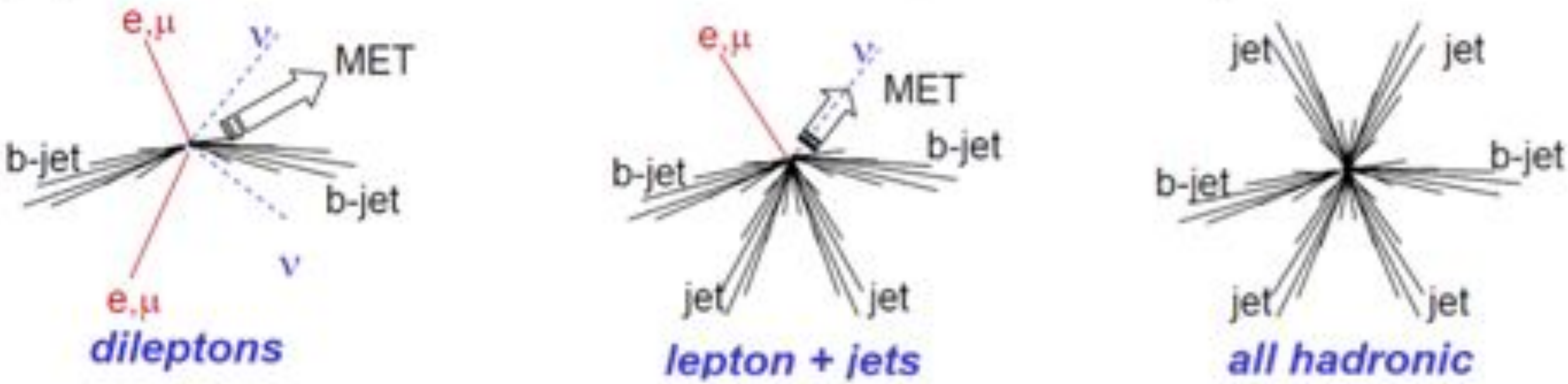
Top decays and backgrounds

slide adapted from FP. Schilling

- Top decays before it can hadronize
  - almost exclusively t->Wb



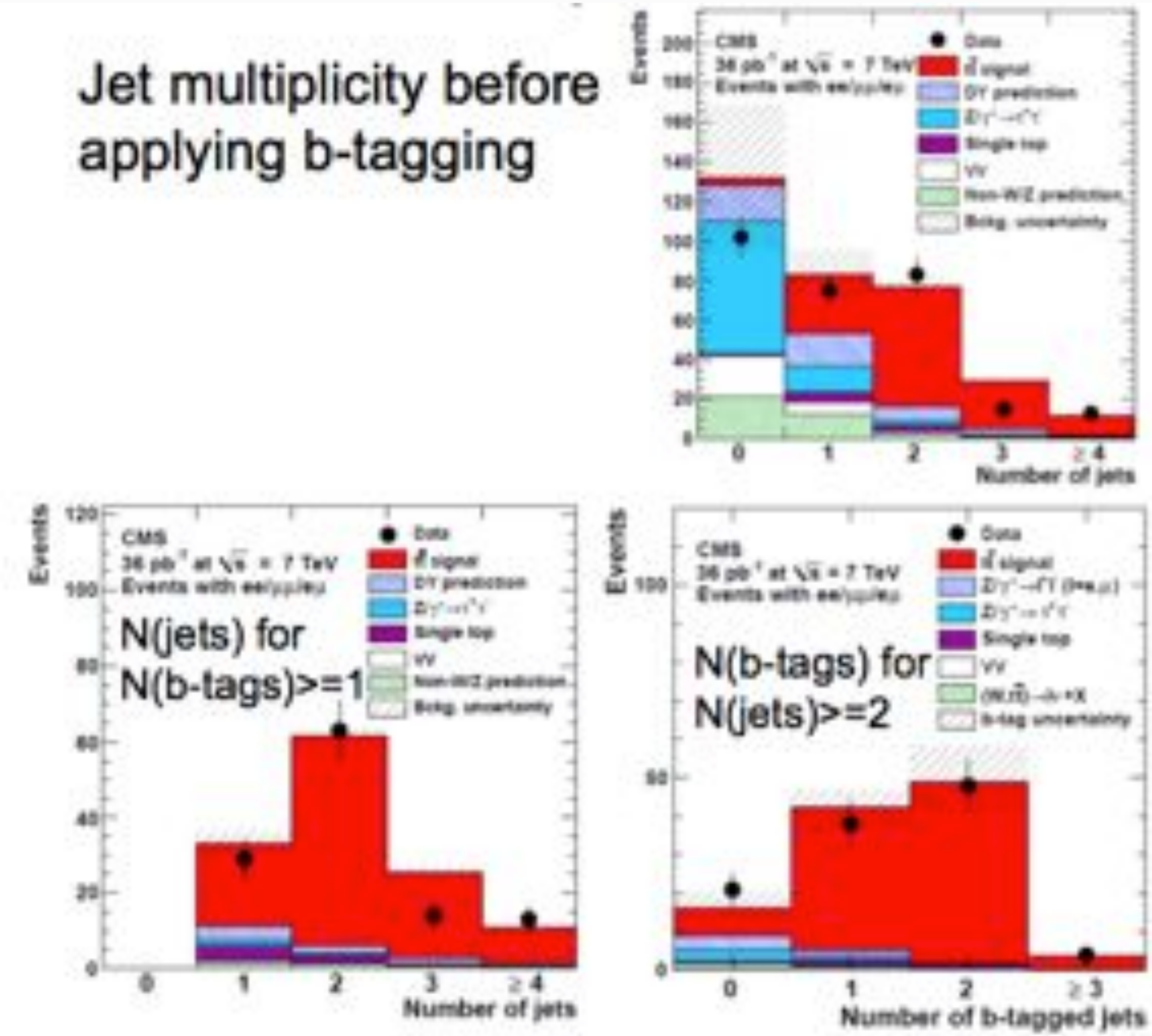
- Top pair event classification according to W decays



Branching ratio:	~5%	~30%	~46%
Backgrounds:	few (mainly Z+jets)	moderate (mainly W+jets)	huge (mainly QCD)

Cross section: Di-Lepton channel

slide adapted from FP. Schilling



Hatched: BG uncertainty

Very pure sample of top events!

CTEQ

Cross section: semi-leptonic channel

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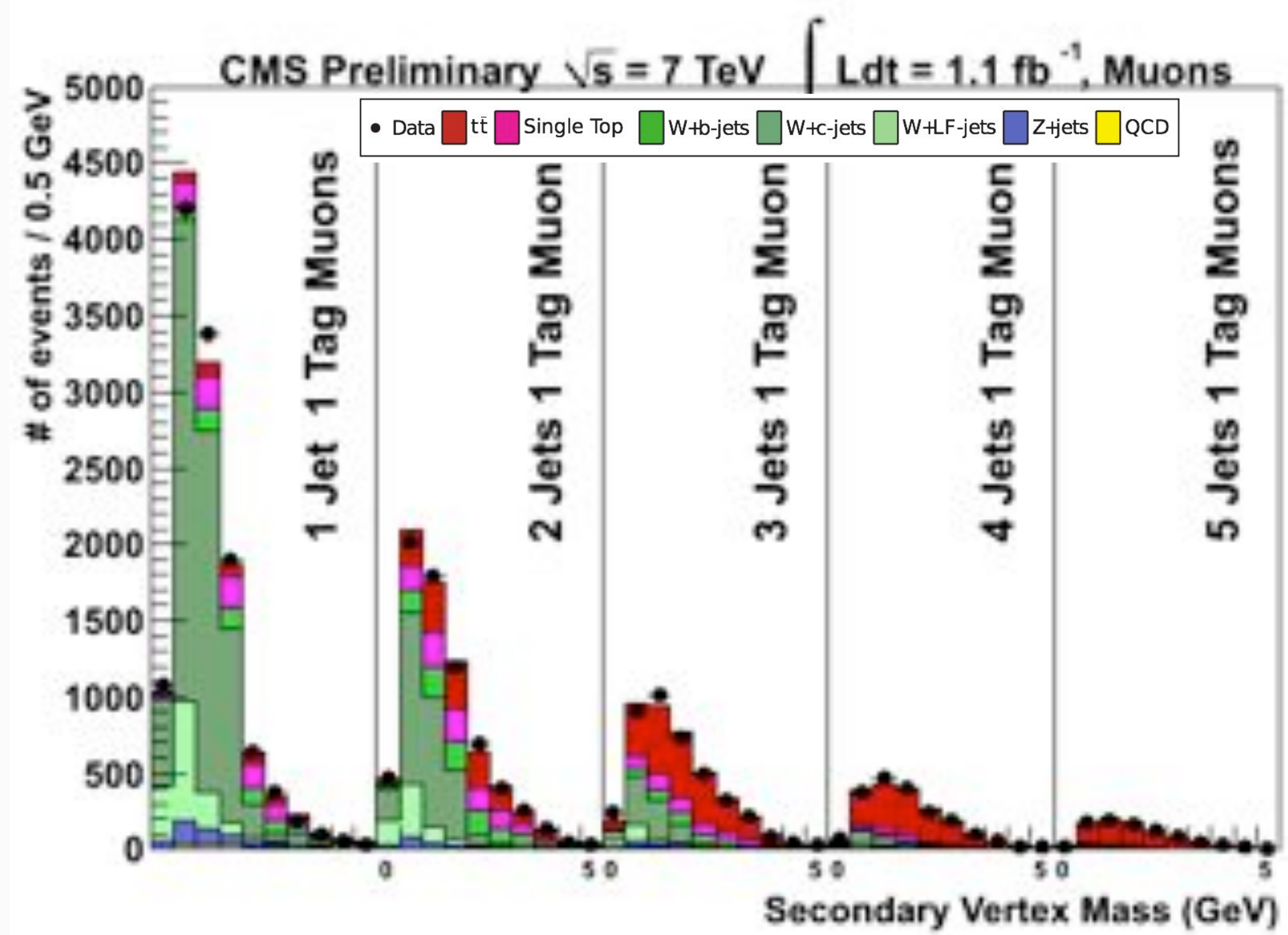
CMS TOP-11-003

Lepton+jets, b-tagged

- divide sample into distinct categories: Nr. jets, Nr. of b-tags, electrons, muons
- fit the secondary vertex mass distribution, using templates, simultaneously in all categories
- let also data/MC scale factors (JES, b-tag eff, W+j Q^2-scale) float in the fit
- **Result**:
  - top cross section, with **syst. uncert. at the 7% level !**
  - scale factors consistent with 1, within the fit error

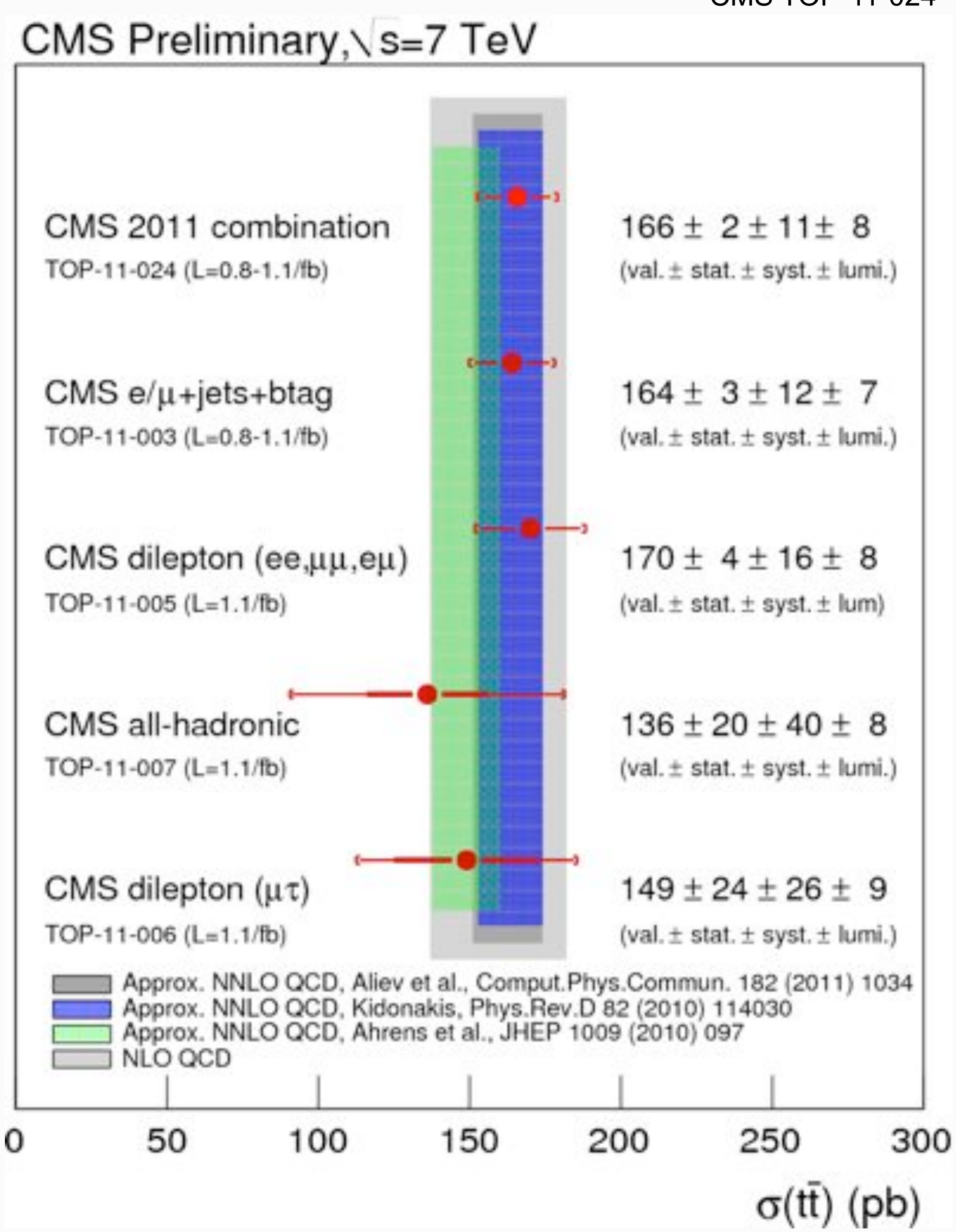


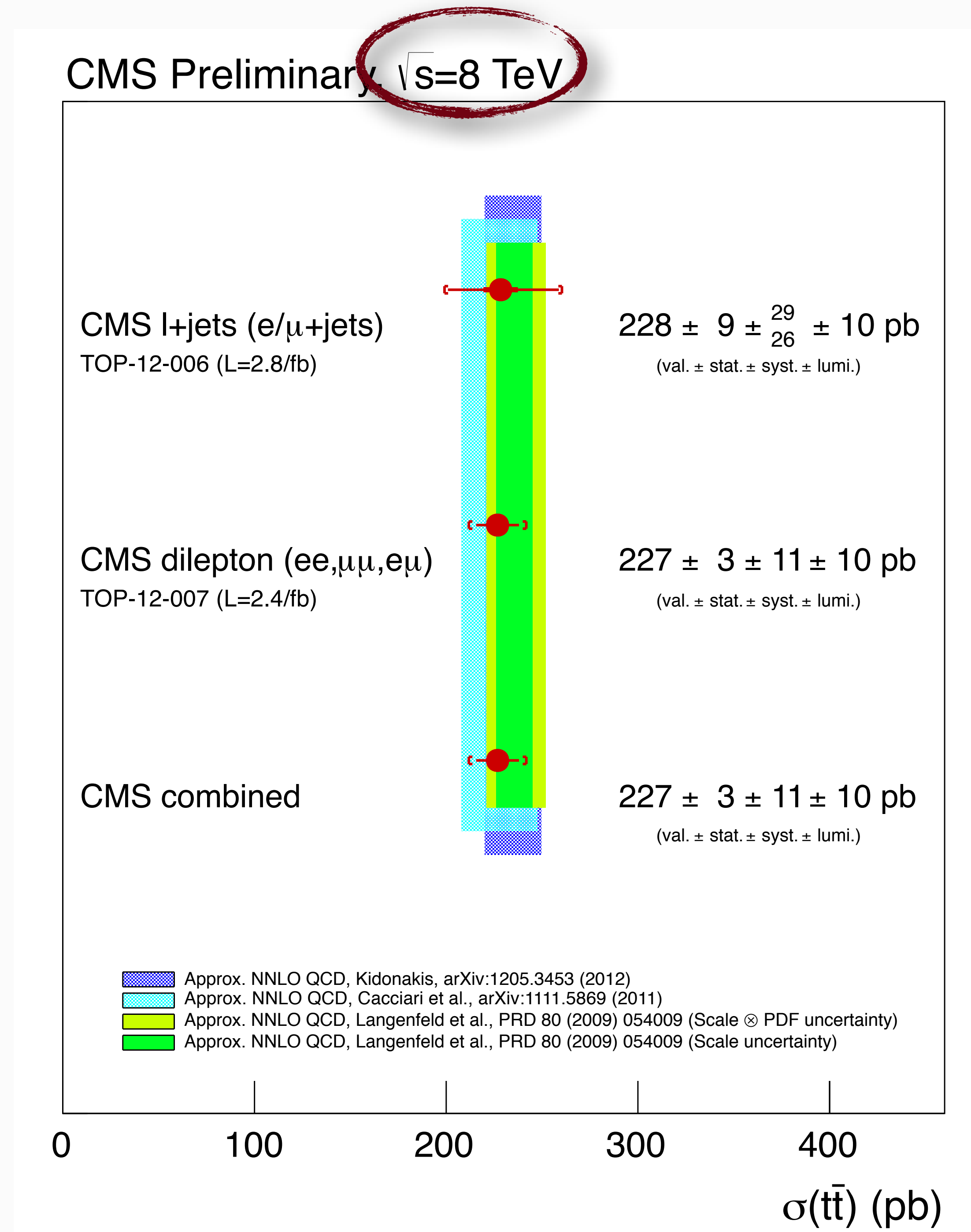
Source	Muon Analysis	Electron Analysis	Combined Analysis
Quantity	Uncertainty (%)		
Lepton ID/reco/trigger	3.4	3	3.4
$\not{E}_T$ resolution due to unclustered energy	< 1	< 1	< 1
$t\bar{t}$+jets Q^2 scale	2	2	2
ISR/FSR	2	2	2
ME to PS matching	2	2	2
Pile-up	2.5	2.6	2.6
PDF	3.4	3.4	3.4
Profile Likelihood Parameter	Uncertainty (%)		
Jet energy scale and resolution	4.2	4.2	3.1
b-tag efficiency	3.3	3.4	2.4
W+jets Q^2 scale	0.9	0.8	0.7
Combined	7.8	7.8	7.3

A fantastic proof of the excellent understanding of all relevant physics objects, and of their outstanding MC description

Top cross section

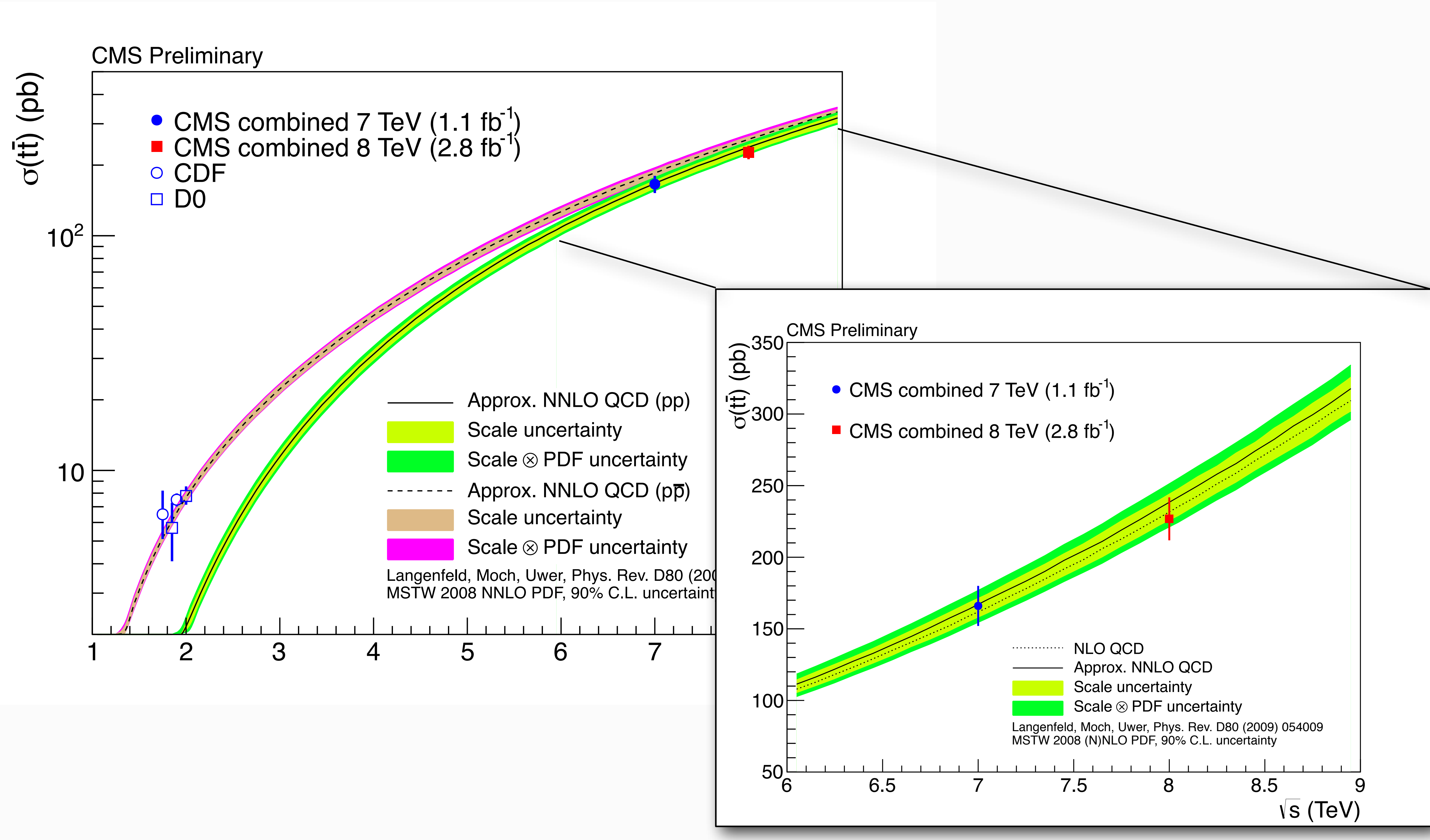
CMS TOP-11-024





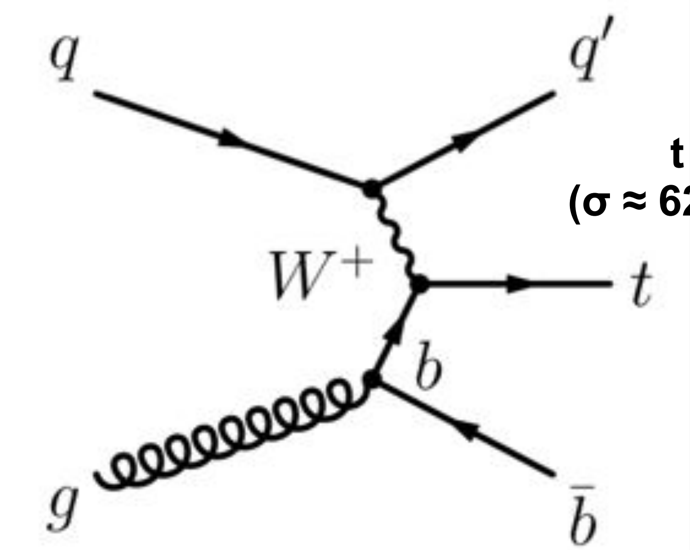
- exp. uncertainty reached 6-7% (!) level, ~ or smaller than theory uncertainty.
- overall impressive agreement with pQCD pred.
- top pair xsec useful to constrain pdfs?

Top cross section



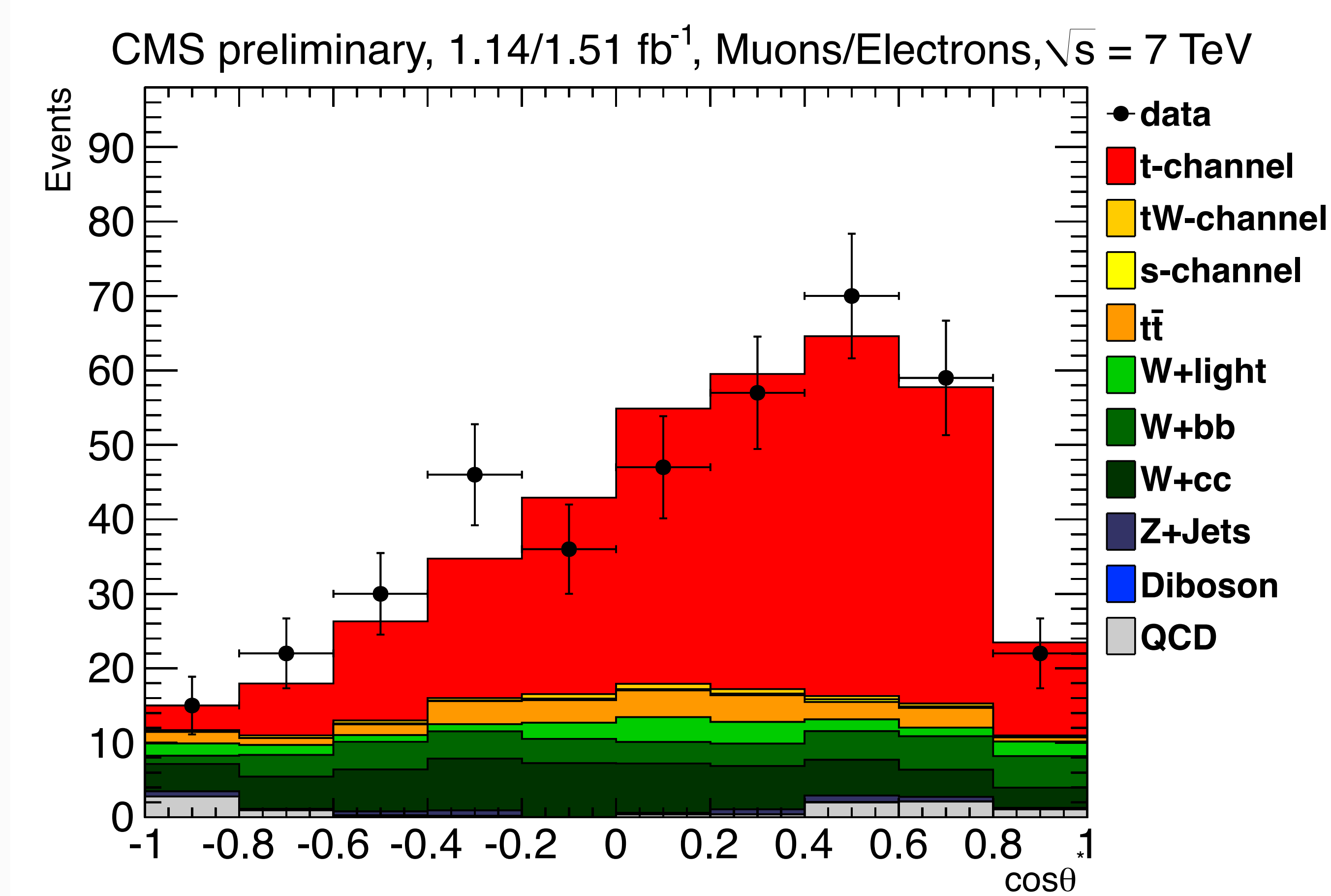
Single top production

CMS TOP-11-021

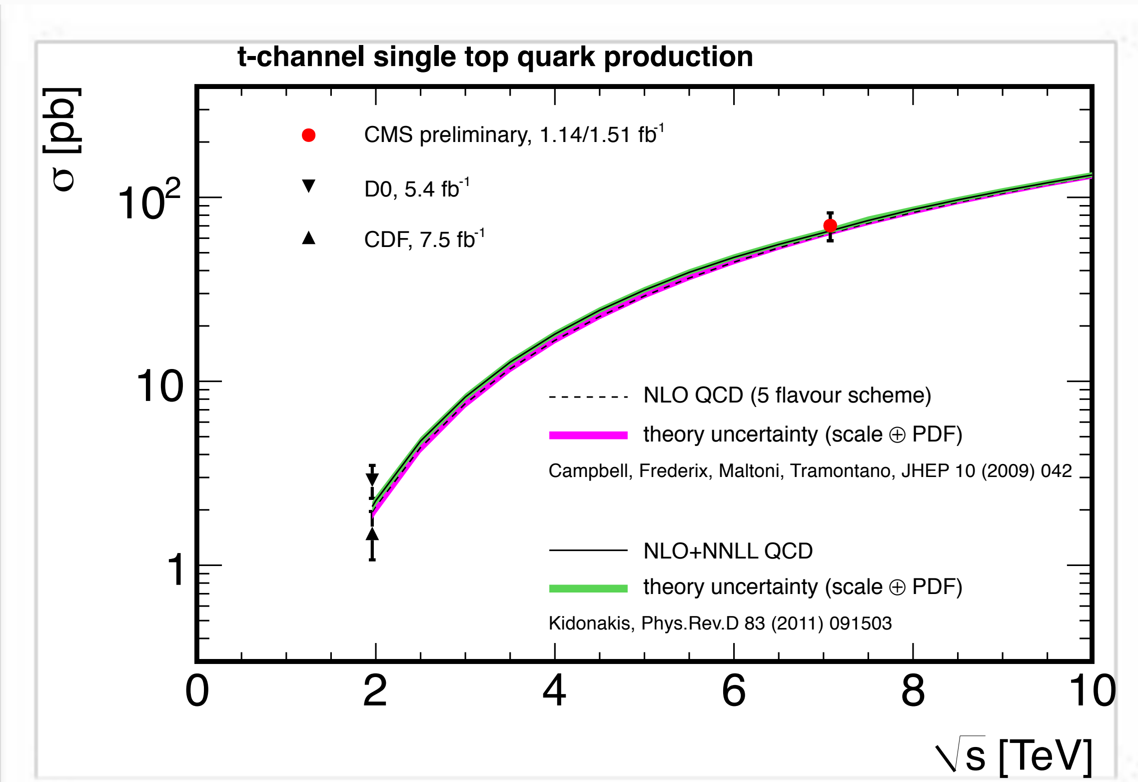


t channel
(σ ≈ 62 pb @ 7 TeV)

- Better than 20% accuracy reached.
- CMS : $|V_{tb}|$ extracted at the 10% level!
- closing in on tW and s-channel prod.



angle between lepton and light jet, in t rest frame



An example of finding **tiny** signals with leptons, MET, b-tag & jets

Showing the readiness for challenging searches such as low-mass Higgs

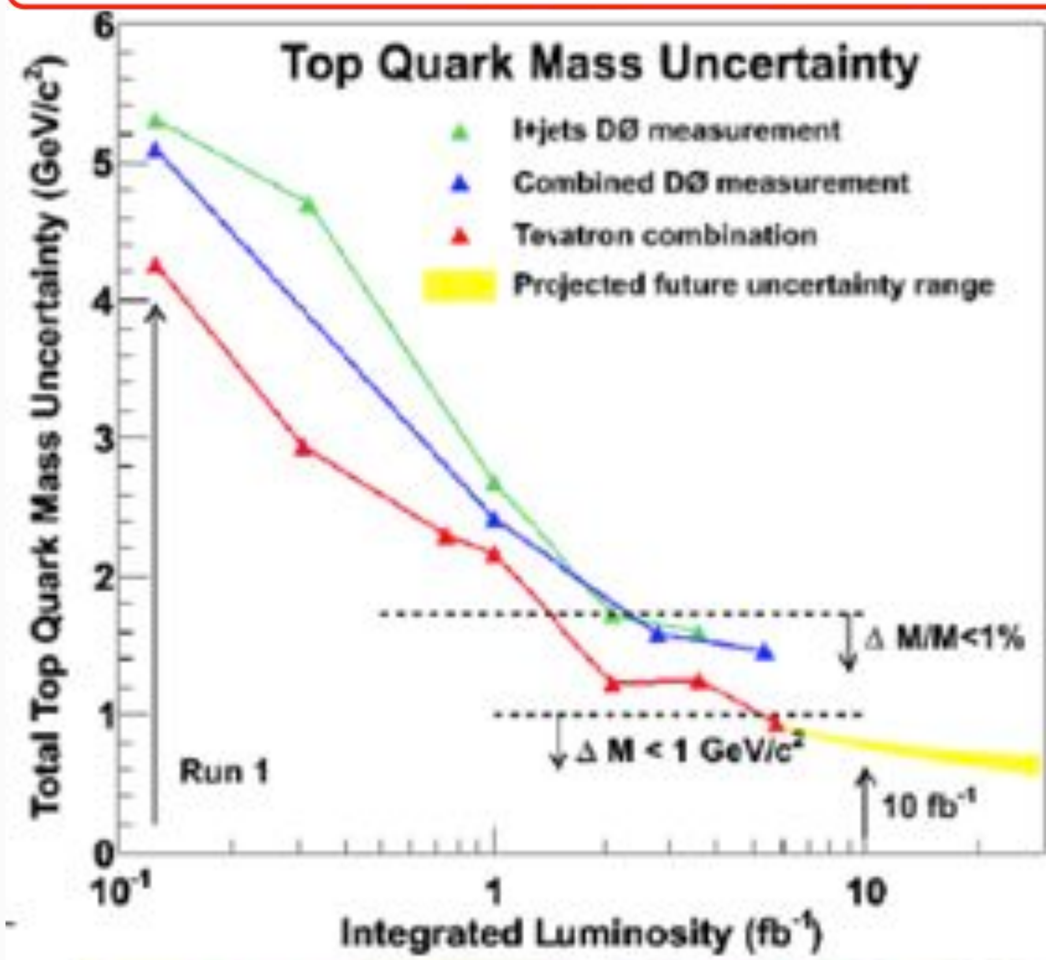
TOP mass

results shown at Moriond QCD

ETH Institute for Particle Physics

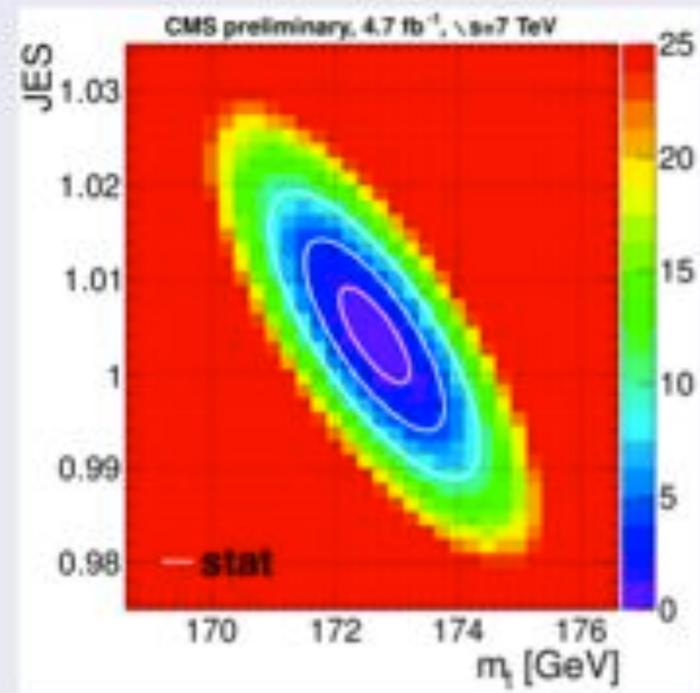
- Tevatron is leading, with LHC catching up....

$$m_{\mathrm{top}} = 173.2 \pm 0.6\,(\mathrm{stat}) \pm 0.8\,(\mathrm{syst})$$



Relative uncertainty: 0.54%
Expect this limit to be improved...

Results on data (4.7 fb^{-1})



$$m_t = 172.6 \pm 0.6_{\mathrm{stat}} \pm 1.2_{\mathrm{syst}}\ \mathrm{GeV}$$

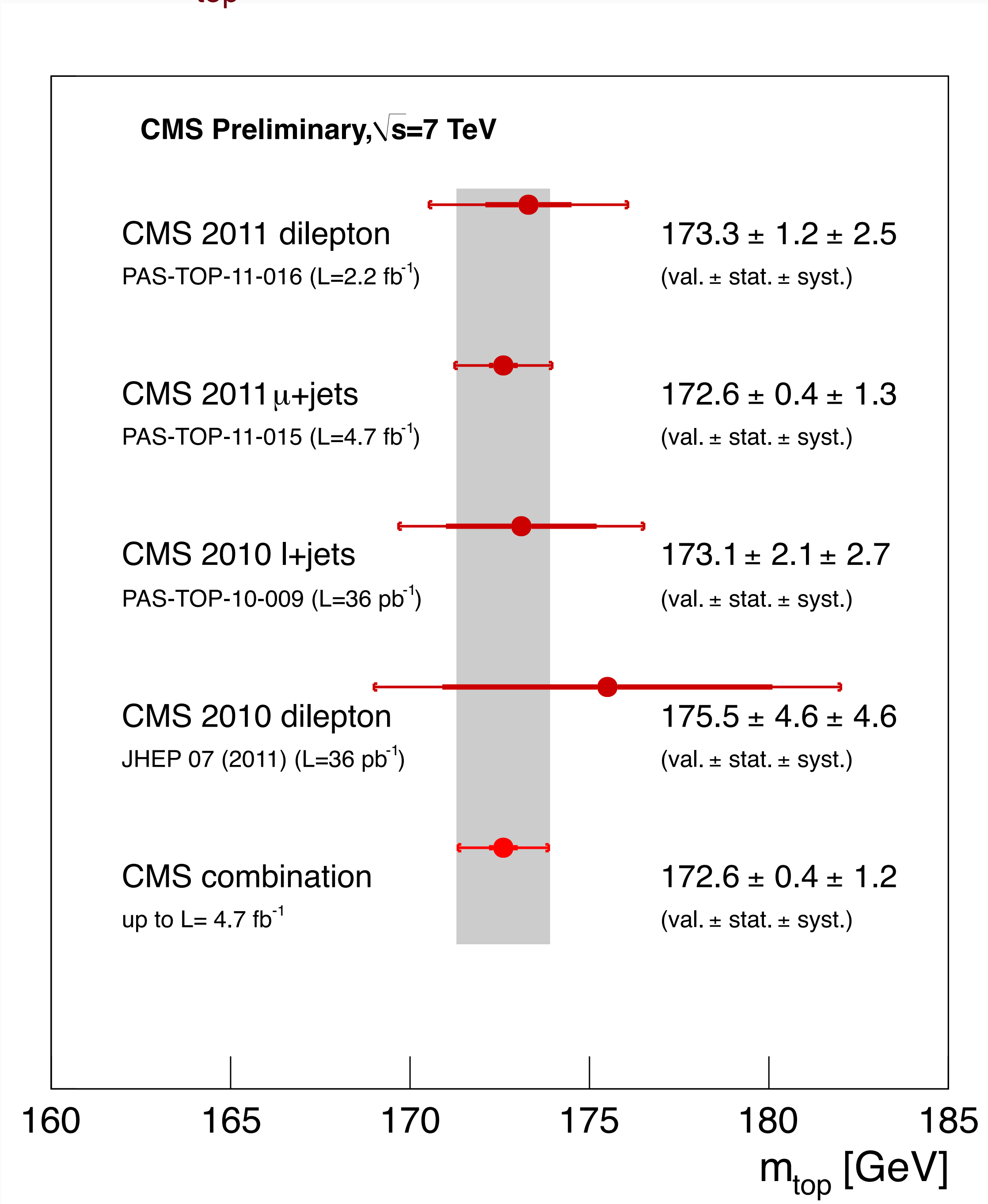
- Most precise LHC measurement

In this Moriond result not yet included:
Systematics due to colour rec, UE

Systematics dominated by JES

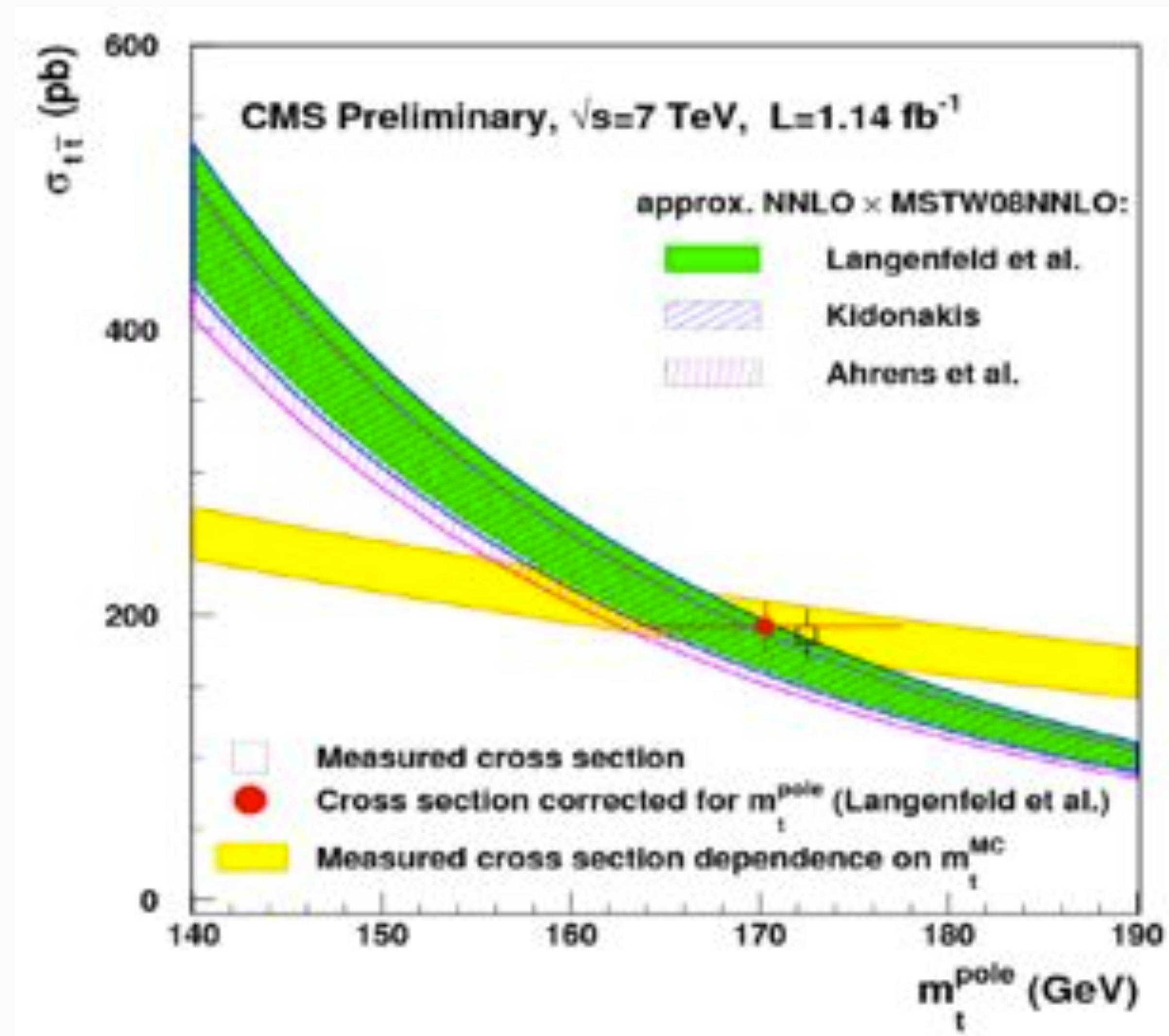
Mass determination

Direct m_{top} reconstruction



From cross section dependence on m_{top}

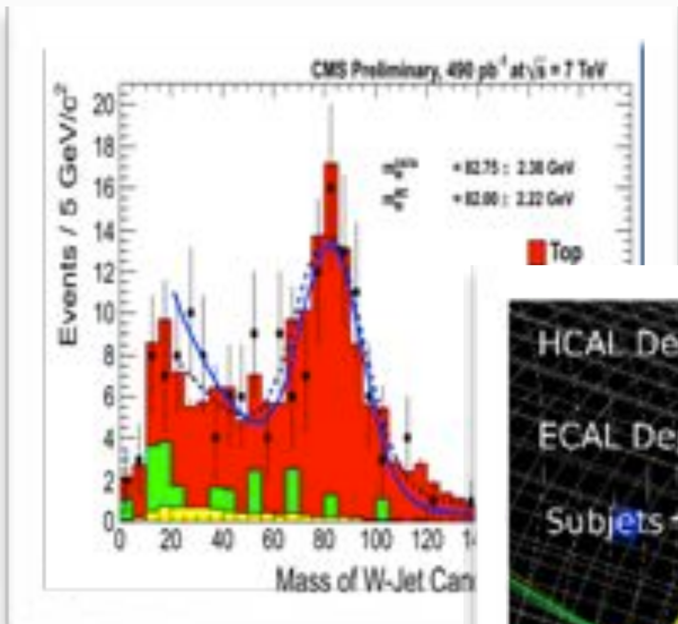
interesting, independent alternative; extract well defined mass parameter, eg. in MSbar scheme. But: theory uncertainties enter.

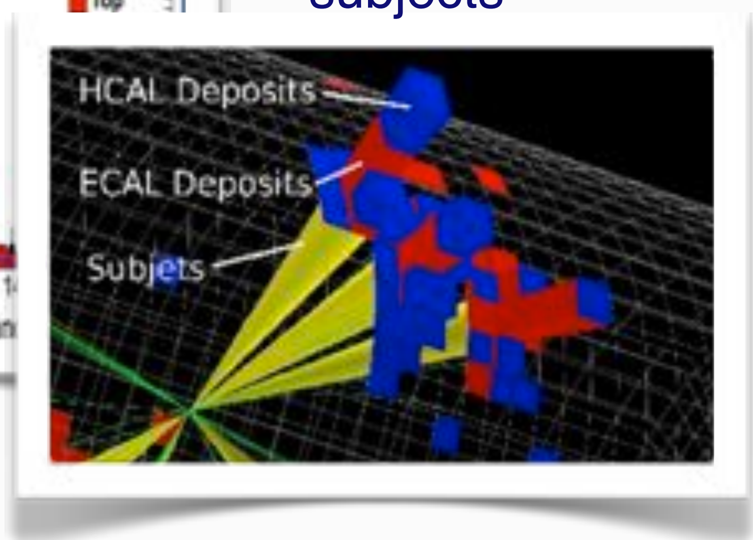


Approx. NNLO × MSTW08NNLO	m_t^{pole} / GeV	m_t^{MS} / GeV
Langenfeld et al. [7]	$170.3^{+7.3}_{-6.7}$	$163.1^{+6.8}_{-6.1}$
Kidonakis [8]	$170.0^{+7.6}_{-7.1}$	–
Ahrens et al. [9]	$167.6^{+7.6}_{-7.1}$	$159.8^{+7.3}_{-6.8}$

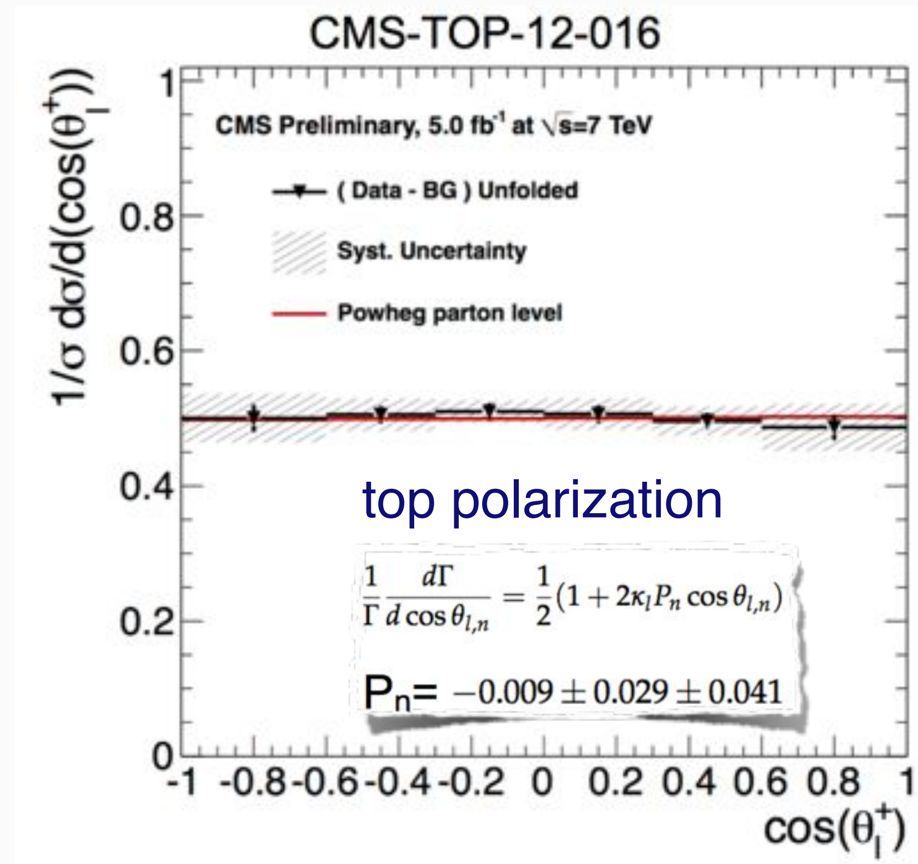
Then: going more differential......

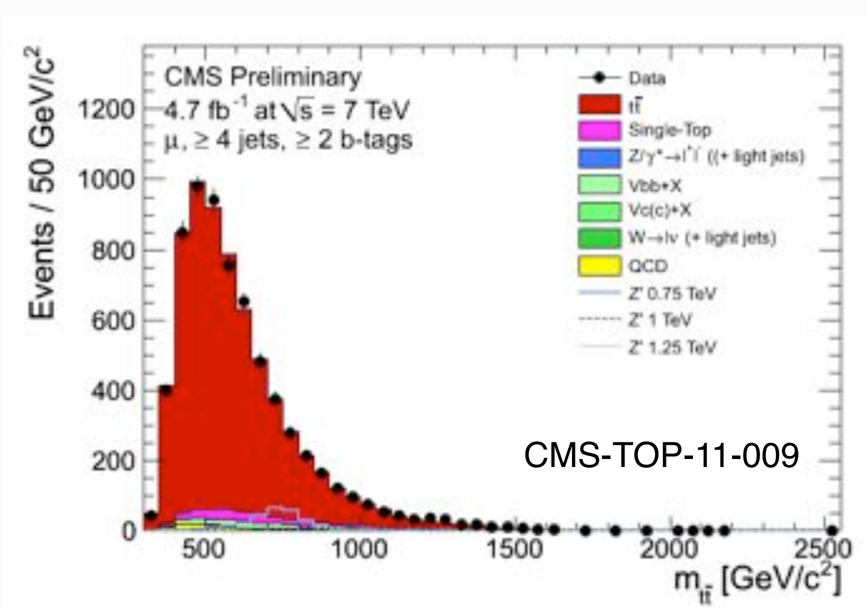
- Many many properties and differential distributions measured
  - spin correlations, W helicity/pol., V_{tb}, m_t-m_{tbar}, top charge, top polarization, charge asymmetry, FCNC, high-mass ttbar pairs (resonances)
  - No anomalies seen so far. Here some examples:

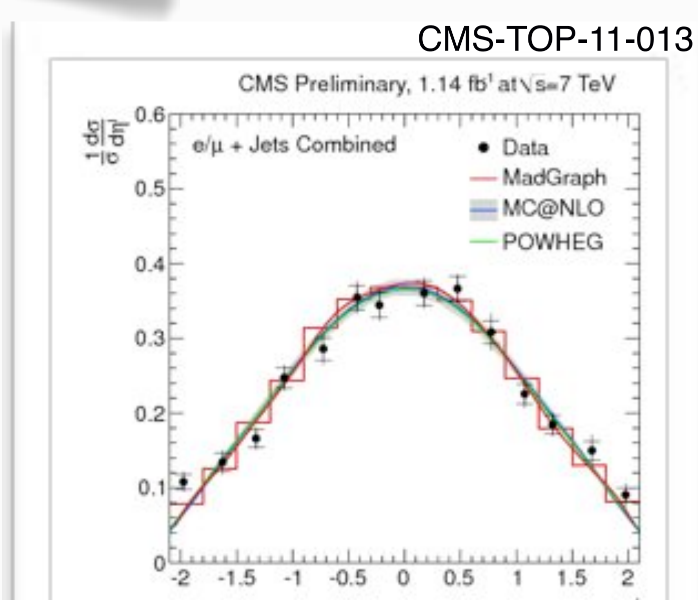




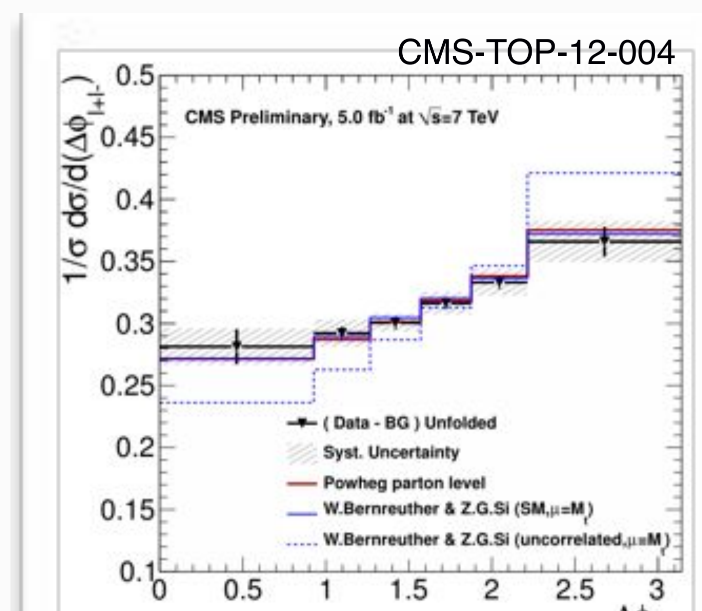
boosted tops,
top tagging,
subjects







lepton rap. in l+jets



spin correlations

A first: TTbar + V production

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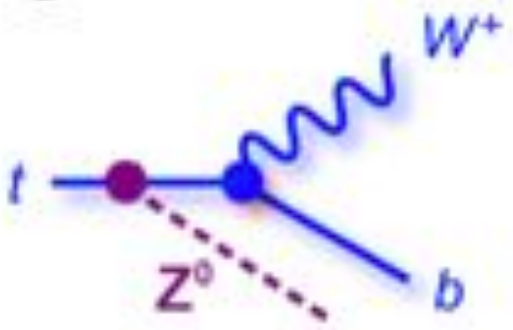
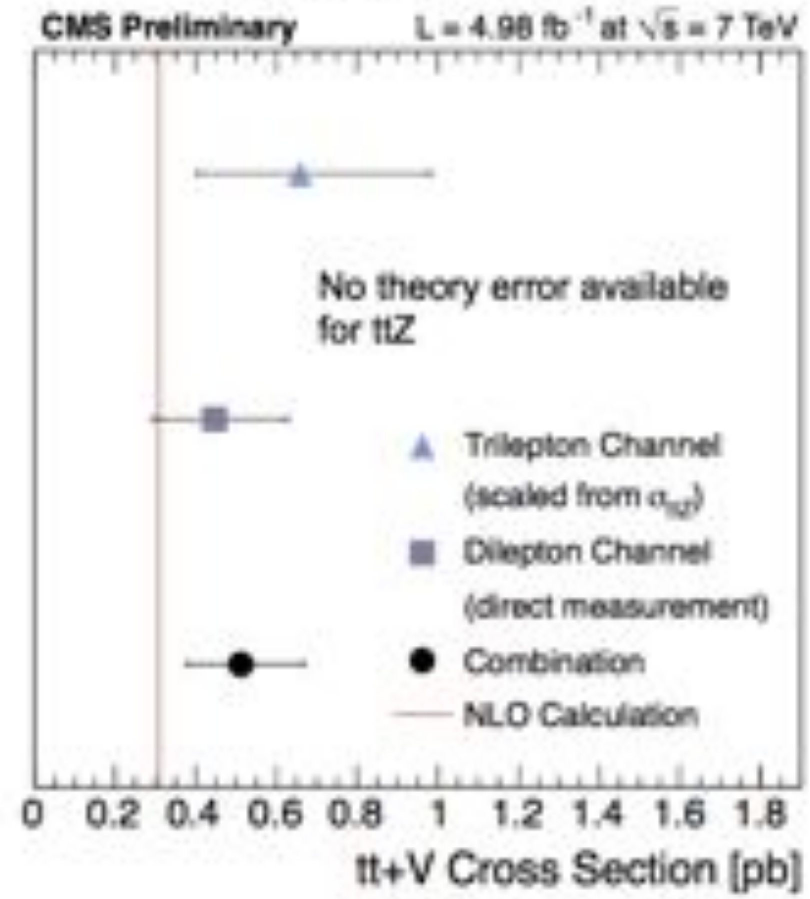
slide adapted from P. Meridiani

Starting to observe associated production of top pairs with W or Z



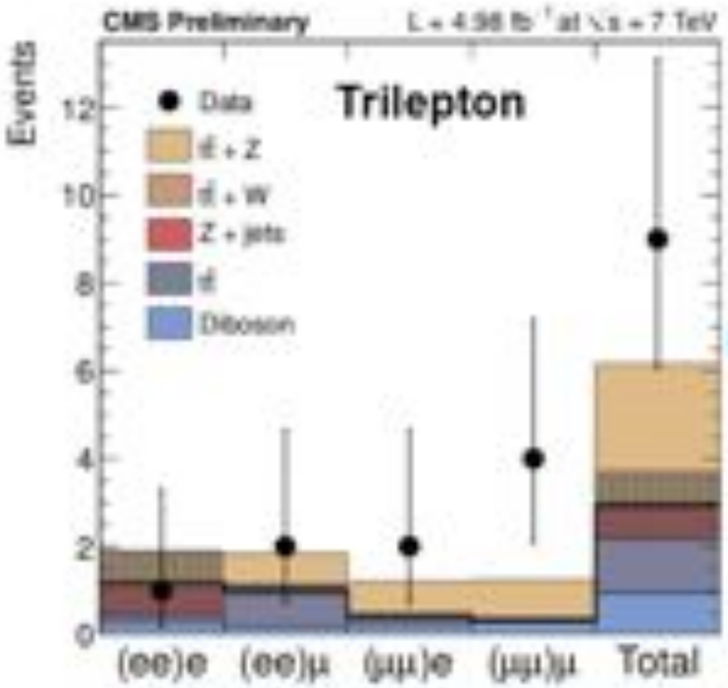
$$\frac{\sigma(t\bar{t})}{\sigma(t\bar{t}+V)} \approx 500$$

CMS-TOP-12-014



Trilepton channel: $\sigma(t\bar{t}Z \to l + \text{jets} + (Z \to ll))$

Same-sign dilepton channel: $\sigma(t\bar{t}V \to l + \text{jets} + (W \to l\nu) \text{ or } (Z \to ll))$



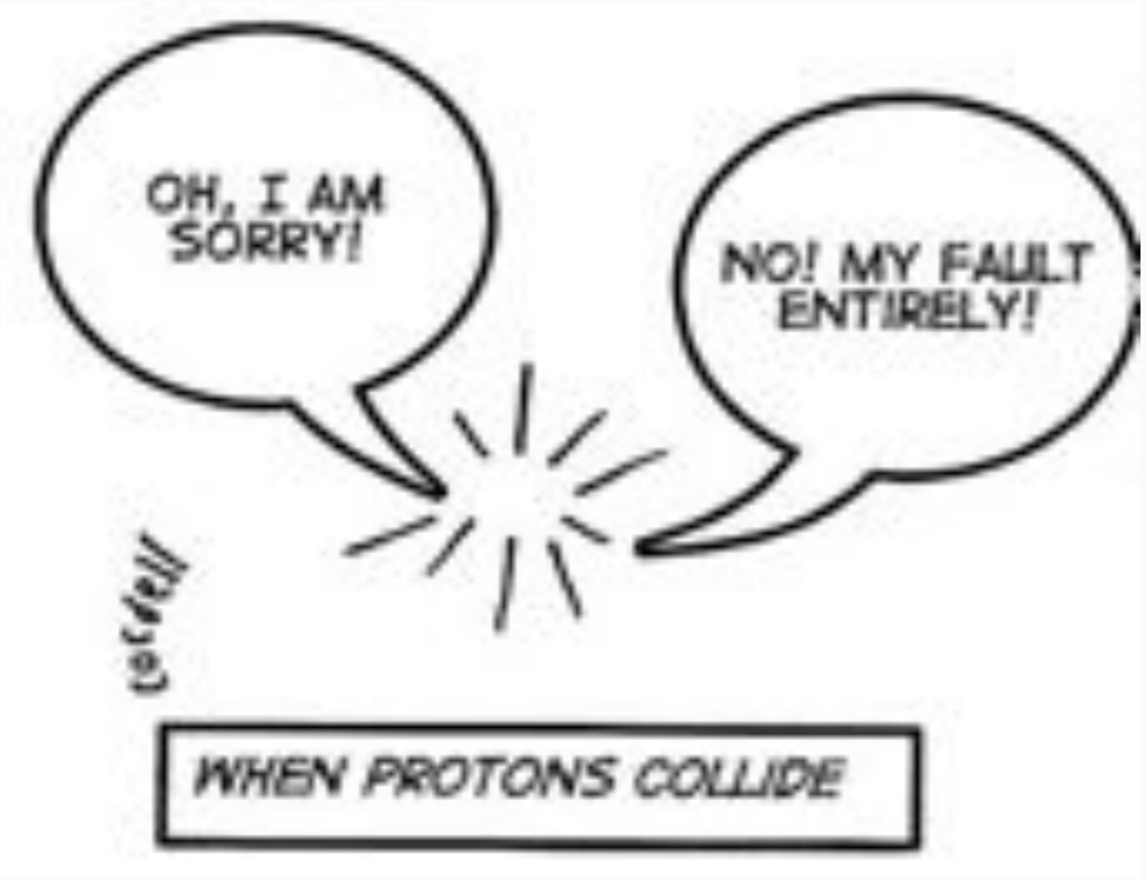
First measurement of *ttV*:

- Result combining all 7 channels:

$$\sigma(t\bar{t}V) = 0.51^{+0.15}_{-0.13}(\text{stat.})^{+0.04}_{-0.02}(\text{syst.})\ \text{pb}$$

→ Significance of 4.67 σ

Summary of Part 1



Summary Part 1

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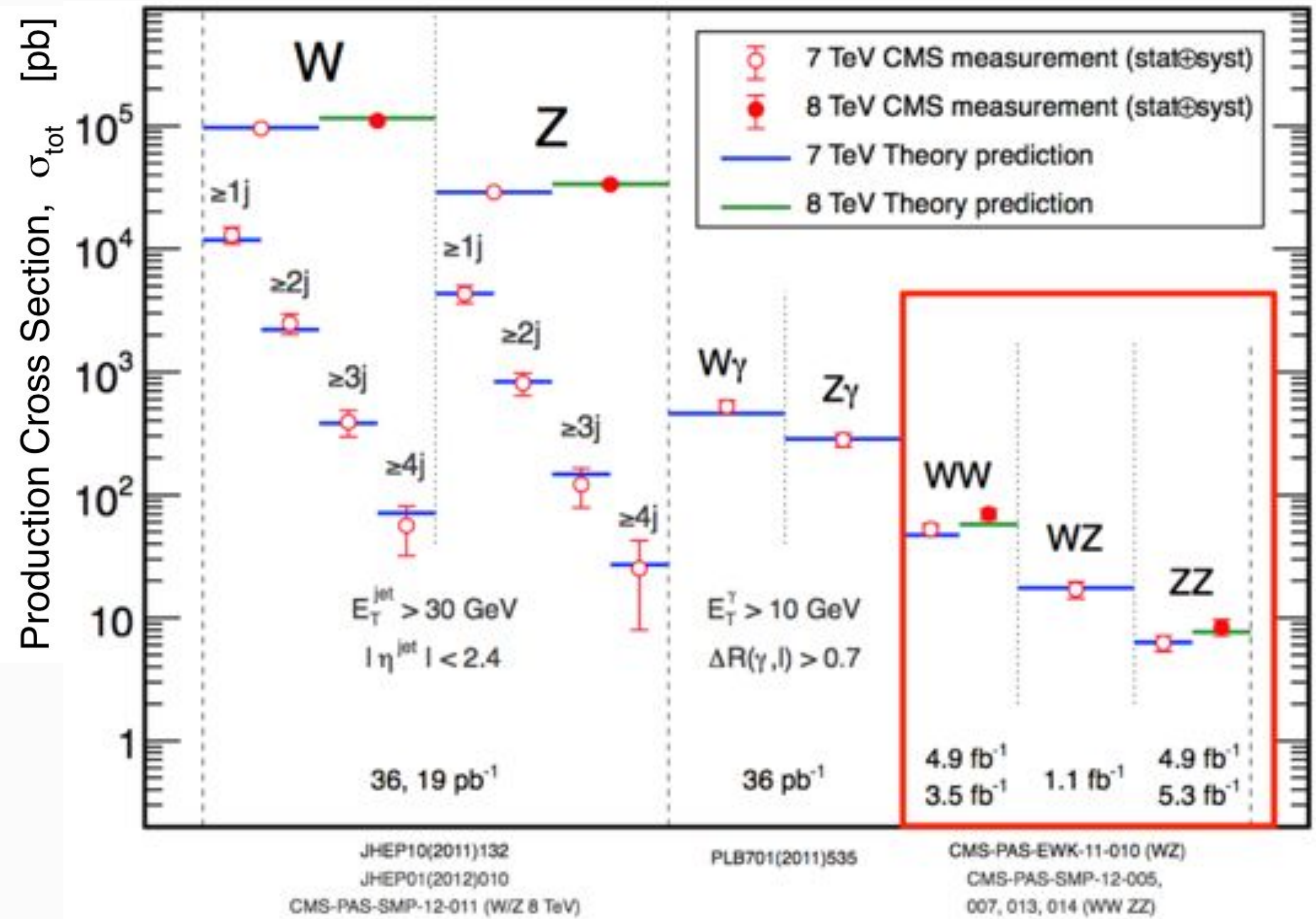


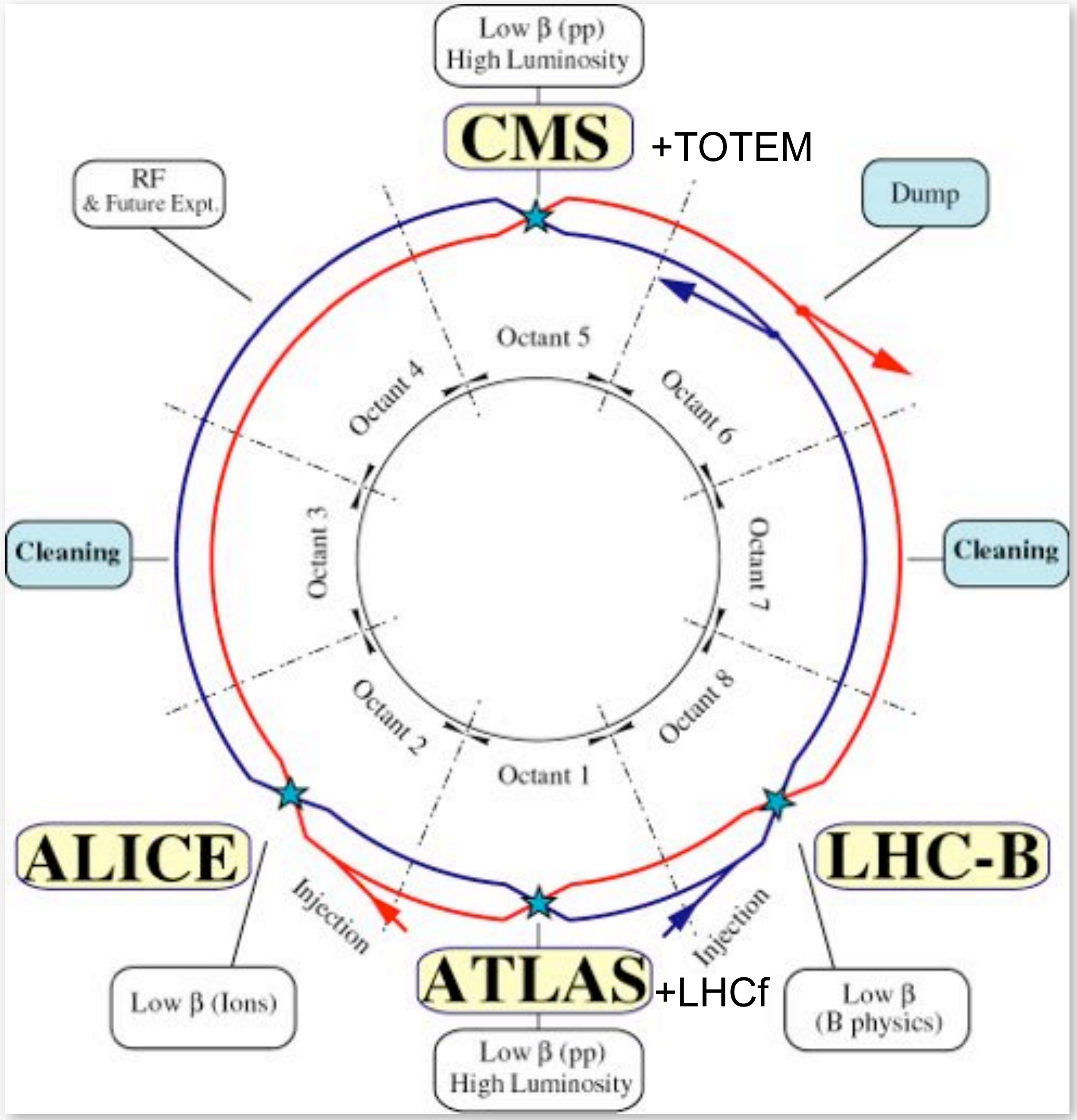
If this is not a success of the SM (and all the theo. and exp. work invested), then what????

Bonus Material

(for free!)

The Machine

The LHC : design parameters



1232 superconducting dipoles
15m long at 1.9 K, B=8.33 T
Inner coil diameter = 56 mm

max. beam-energy	7 TeV	(7x TEVATRON)
design Luminosity	10^{34} cm^{-2}s^{-1}	(>100x TEVATRON)
Bunch spacing	24.95 ns	
Particles/bunch	1.1 10^{11}	
Stored E/beam	362 MJ	

Also : Lead Ions operation
Energy/nucleon 2.76 TeV / u
Total initial lumi 10^{27} cm^{-2} s^{-1}

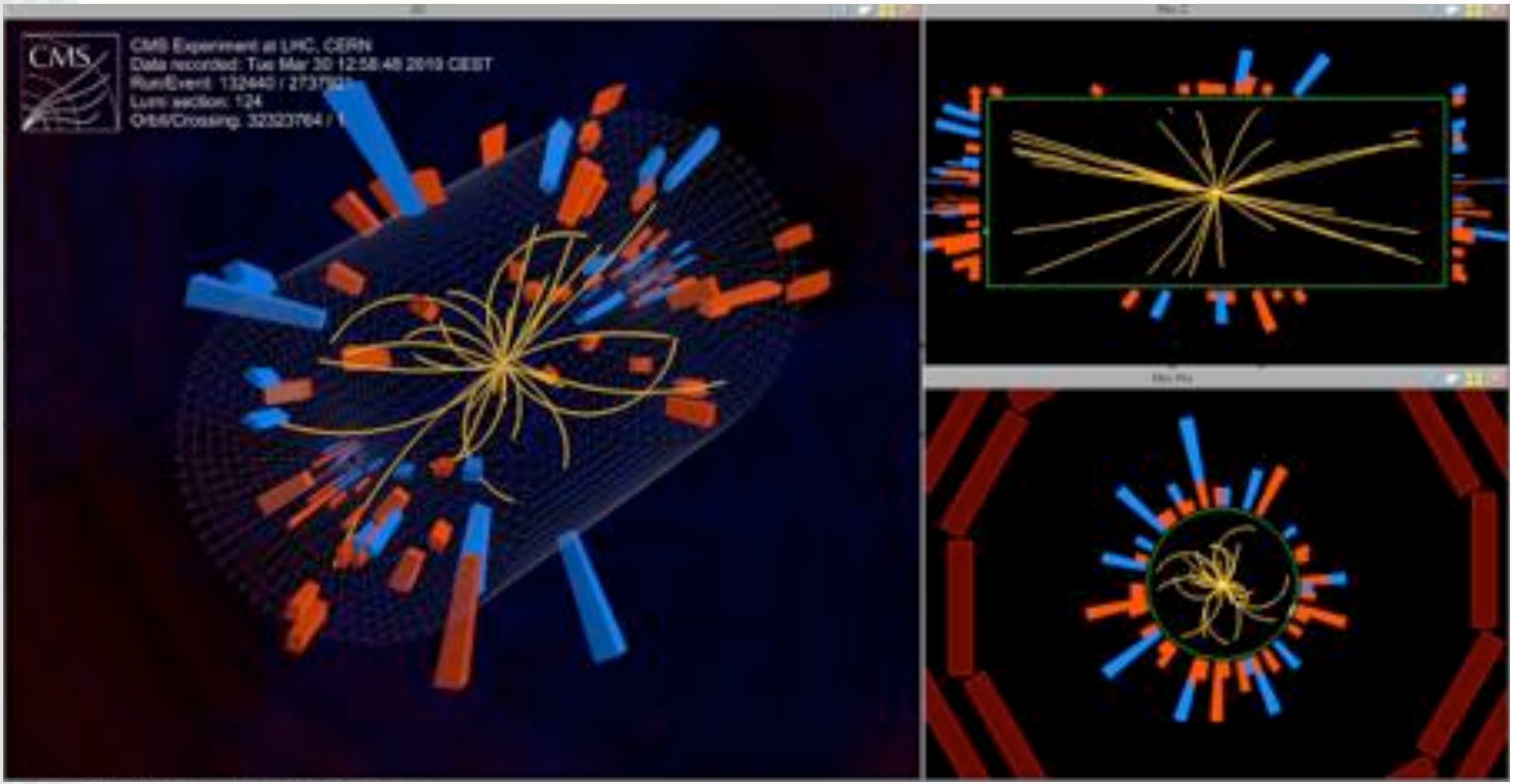
Unprecedented complexity:
10k magnets powered in 1700 electrical circuits

The LHC Start-Up in 2009

- Nov.20: Start of 2009 beam circulation
- Nov. 23: First collisions at 900 GeV
- Nov. 26: First results shown publicly at CERN!
- Dec.6: First physics fills
- Dec.8: Acceleration
  - both beams ramped to 1.18 TeV each
- Dec.11: Higher proton intensities (7E10)
  - Starting to accumulate luminosity at 900 GeV
- Dec.14, Collisions at 2.36 TeV !

First CMS Collision Event

First collisions in CMS at 7 TeV



within seconds: registered, reconstructed and displayed on screens

LHC : Performance Limitations

Parameter/Effects	Limitations	Now
Beam energy limited by maximum dipole field. Industrially available technology.	7 TeV	3.5 -> 4 TeV
Bunch and total beam intensity beam-beam effect (tune spread), small allowed space in Q-space, collimators (impedance, collective instabilities), electron cloud, radiation	$N < 1.7\ 10^{11}$ $N_{nom} = 1.15\ 10^{11}$ $I < 0.85$ A	**$N \sim 1.5\ 10^{11}$**
Normalized emittance Limited by injectors and main dipole aperture	$\varepsilon_n < 3.75\ \mu m$	**1.9 - 2.4 μm**
Beam size at IP (β^*) Limited by (triplet) quadrupole aperture	$0.55\ m < \beta^* < 1\ m$ $\sigma \sim 17\ \mu m$	0.6 m $\sigma \sim 20\ \mu m$
Crossing angle Limited by (triplet) quadrupole aperture	300 μrad	290 μrad
Number of (colliding) bunches Limited by stored beam energy, electron cloud eff.	2808	1368
Luminosity	$1\ 10^{34}$	$\sim 6 \times 10^{33}$

Legend:

N : particles/bunch

n : nr. of bunches

I : current / beam

$\varepsilon_n = \varepsilon\gamma$, ε : emittance

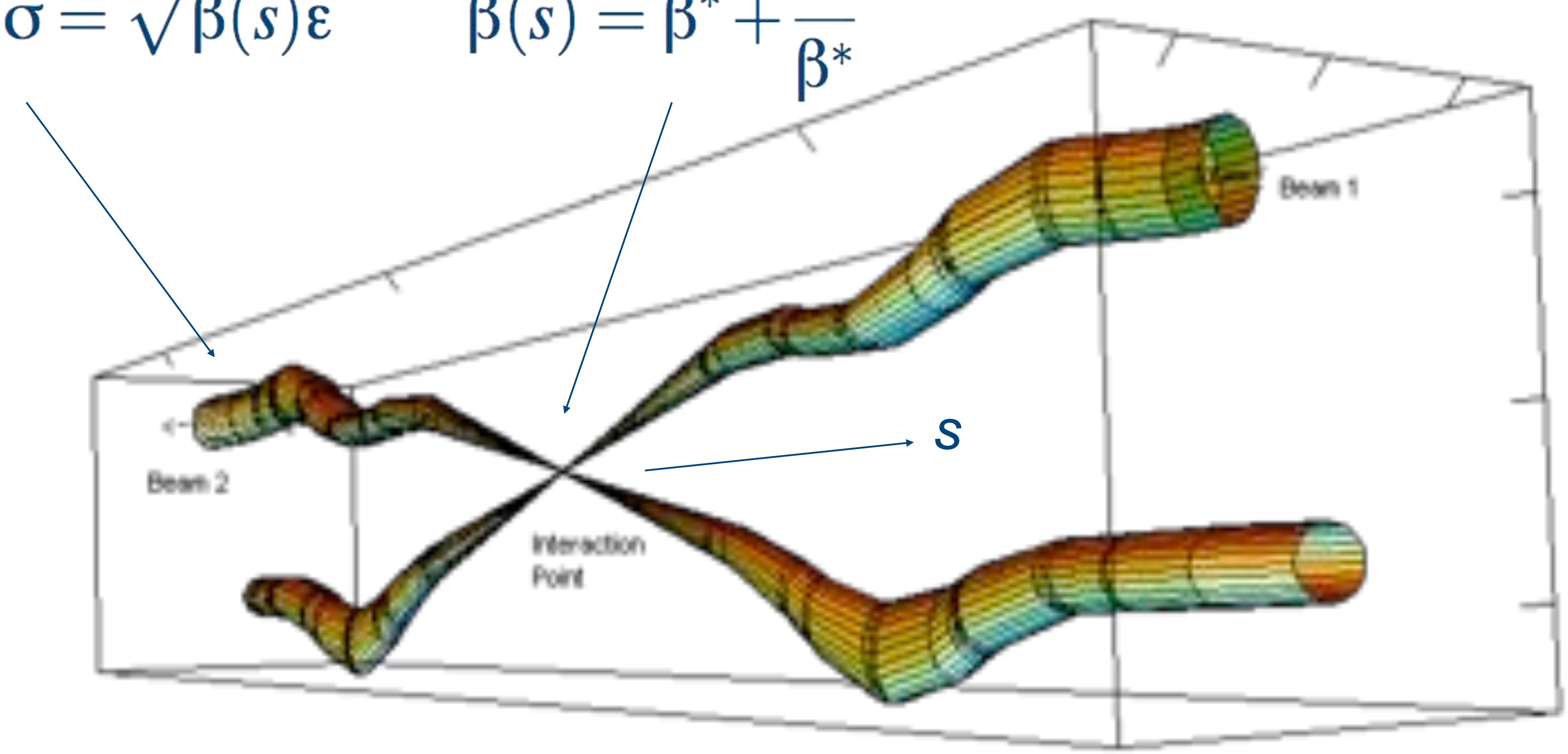
β^* : β at IP

Beam size $\sigma^2 = \beta\varepsilon$

Q : tune (number of trans. oscil./turn)

LHC : Performance Limitations

$$\sigma = \sqrt{\beta(s)\varepsilon} \qquad \beta(s) = \beta^* + \frac{s^2}{\beta^*}$$



Relative beam sizes around IP1 (Atlas) in collision

σ^*=16.6μm ⟶ (~23m) σ(triplet)=1.54 mm

	ow
	TeV
	.5 10^{11}
	2.3 μm
	m 23 μm
Limited by (triplet) quadrupole aperture	μrad
Number of bunches Limited by stored beam energy, electron cloud eff.	
Luminosity	

Legend:

- N : particles/bunch
- n : nr. of bunches
- I : current / beam
- $\varepsilon_n = \varepsilon\gamma$, ε : emittance
- β^* : β at IP
- Beam size $\sigma^2 = \beta\varepsilon$
- Q : tune (number of trans. oscil./turn)

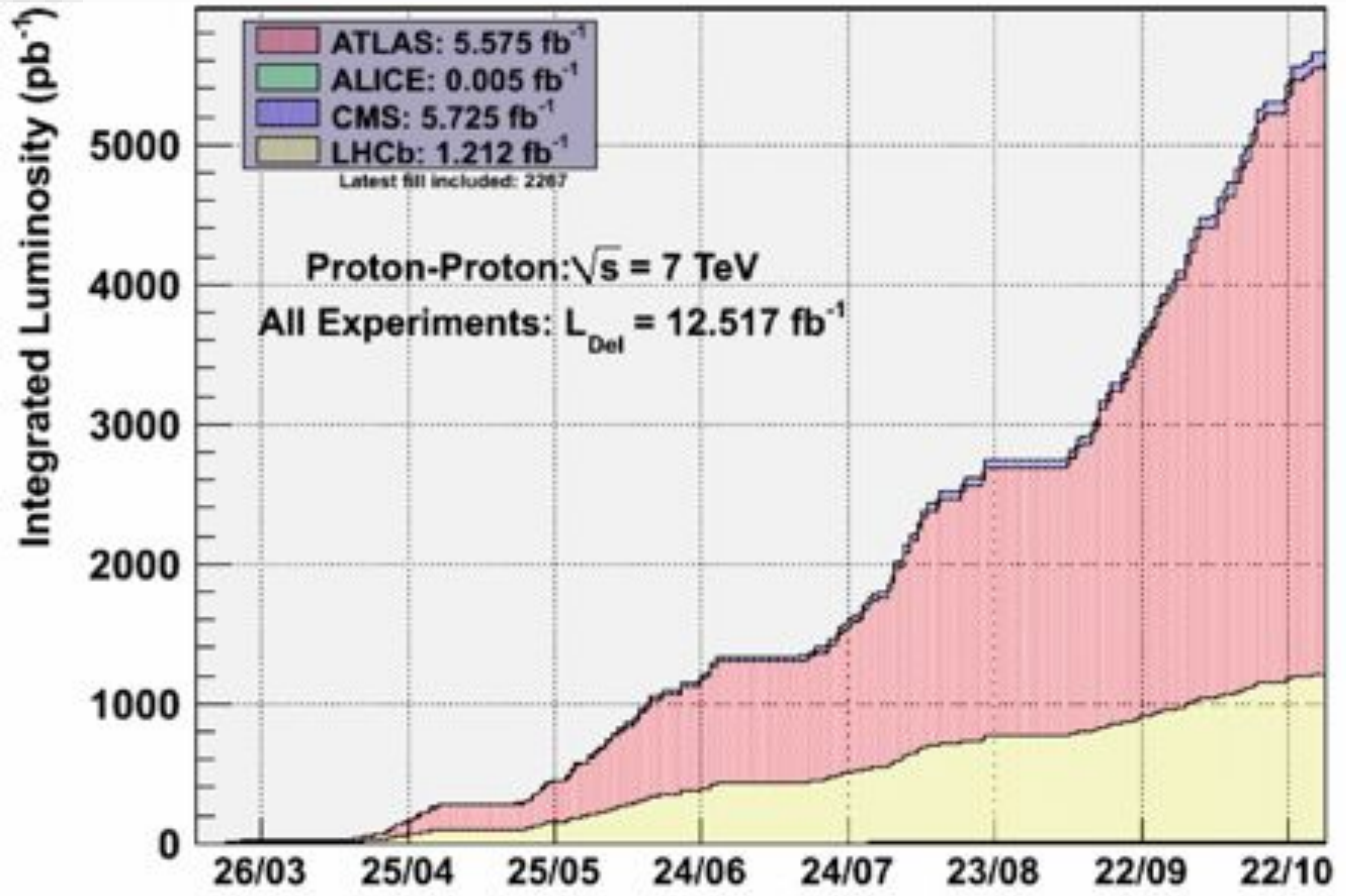
Recent records courtesy ATLAS (18th June 2012)

Peak Stable Luminosity Delivered	6.76×10^{33} $cm^{-2}s^{-1}$
Maximum Luminosity Delivered in one fill	237.32 pb^{-1}
Maximum Luminosity Delivered in one day	250.94 pb^{-1}
Maximum Luminosity Delivered in 7 days	1350.14 pb^{-1}
Maximum Colliding Bunches	1380
Maximum Peak Events per Bunch Crossing	43.81
Maximum Average Events per Bunch Crossing	31.87
Longest Time in Stable Beams for one fill	22.8 hours
Longest Time in Stable Beams for one day	20.5 hours (85.6%)
Longest Time in Stable Beams for 7 days	90.0 hours (53.6%)
Fastest Turnaround to Stable Beams	2.13 hours

Performance in 2011

ETH Institute for Particle Physics

Fournier, HCP2011



Typical efficiency of experiments:

data taking eff >~ 90%

fraction of good quality data ~ 85-90 %

==> ATLAS and CMS have about 4.7 fb^{-1} of good data in hand

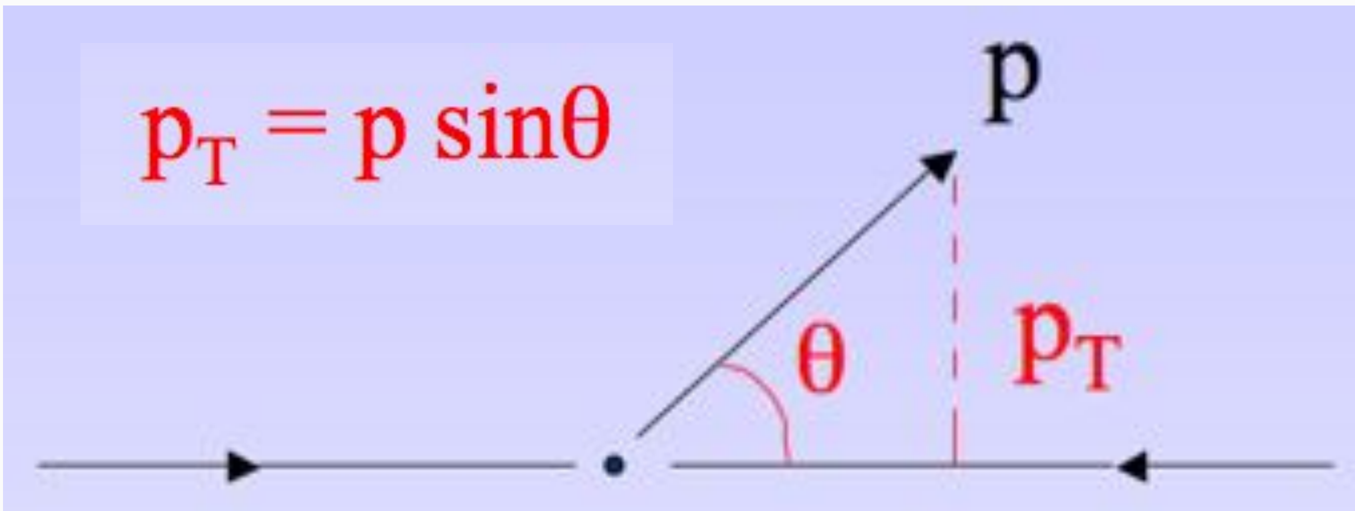
(was ~36 pb^{-1} in 2010)

Factor ~20 gain in peak luminosity w.r.t. 2010, mainly thanks to : number of bunches, beta*, emittance

The experiments: Expectations, requirements, performance

proton - proton collisions are complex....

Variables used in pp collisions

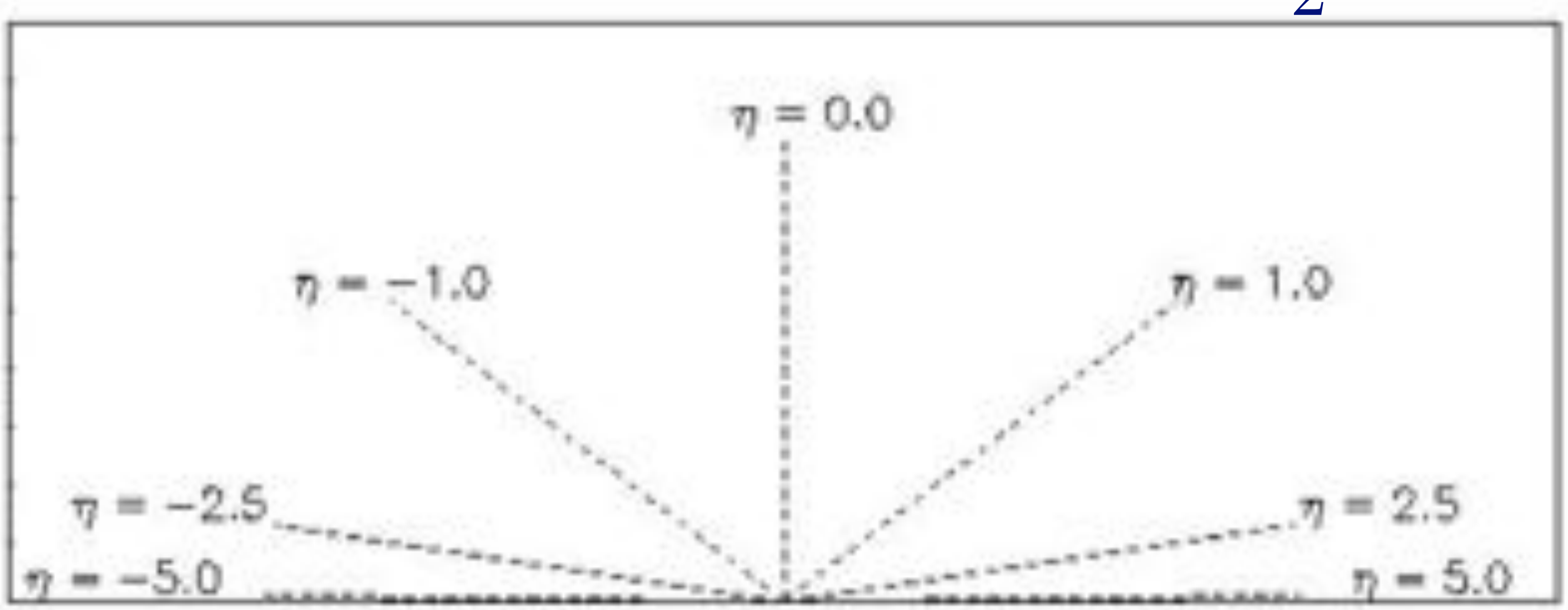


Transverse momentum

(in the plane perpendicular to the beam)

Rapidity $y = \frac{1}{2} \ln\left(\frac{E + p_L}{E - p_L}\right)$

(Pseudo)-Rapidity $\eta = -\ln\tan\frac{\theta}{2}$



$\theta = 90^o \rightarrow \eta = 0$

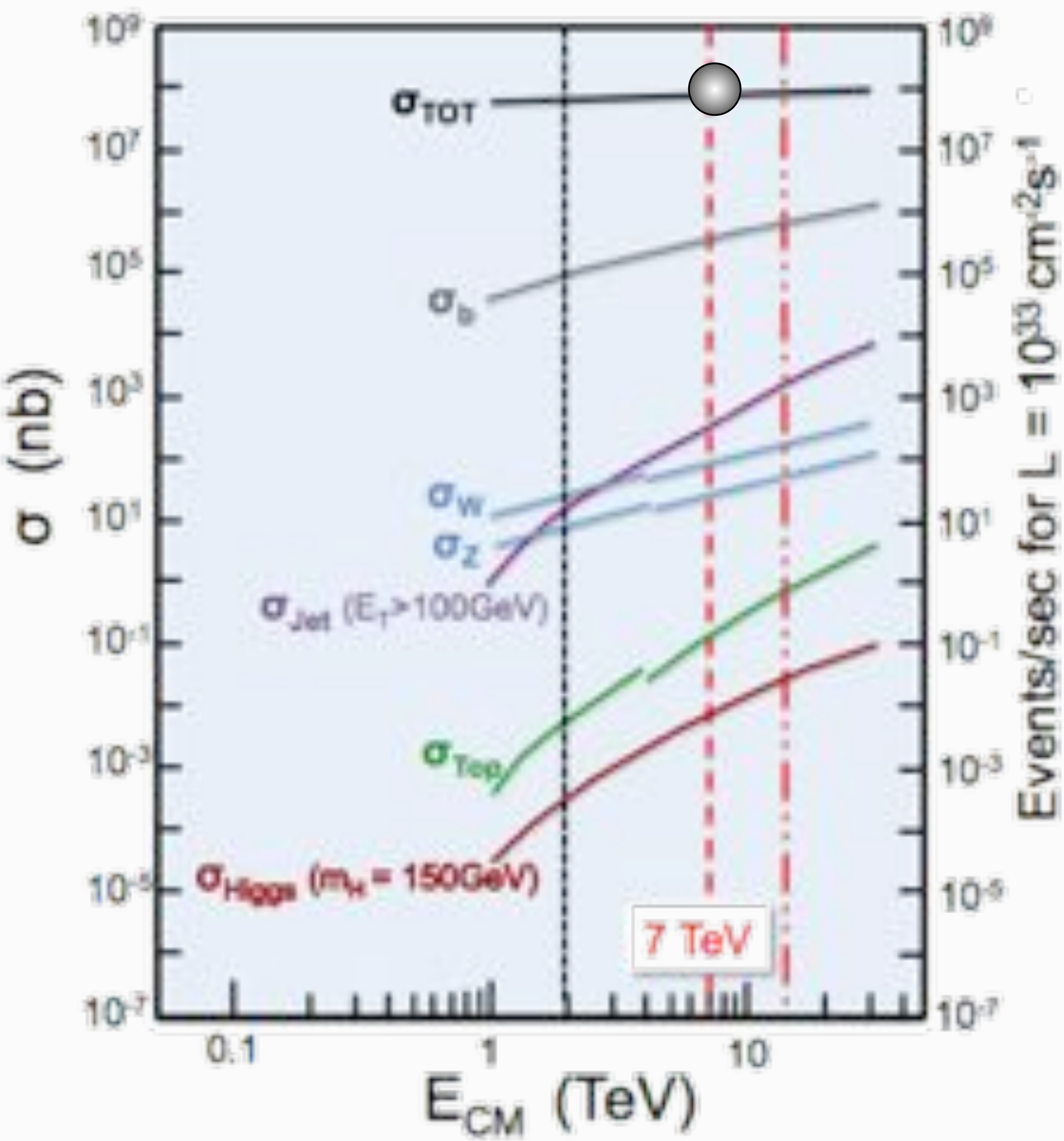
$\theta = 10^o \rightarrow \eta \cong 2.4$

$\theta = 170^o \rightarrow \eta \cong -2.4$

$\theta = 1^o \rightarrow \eta \cong 5.0$

Expected Physics : 1

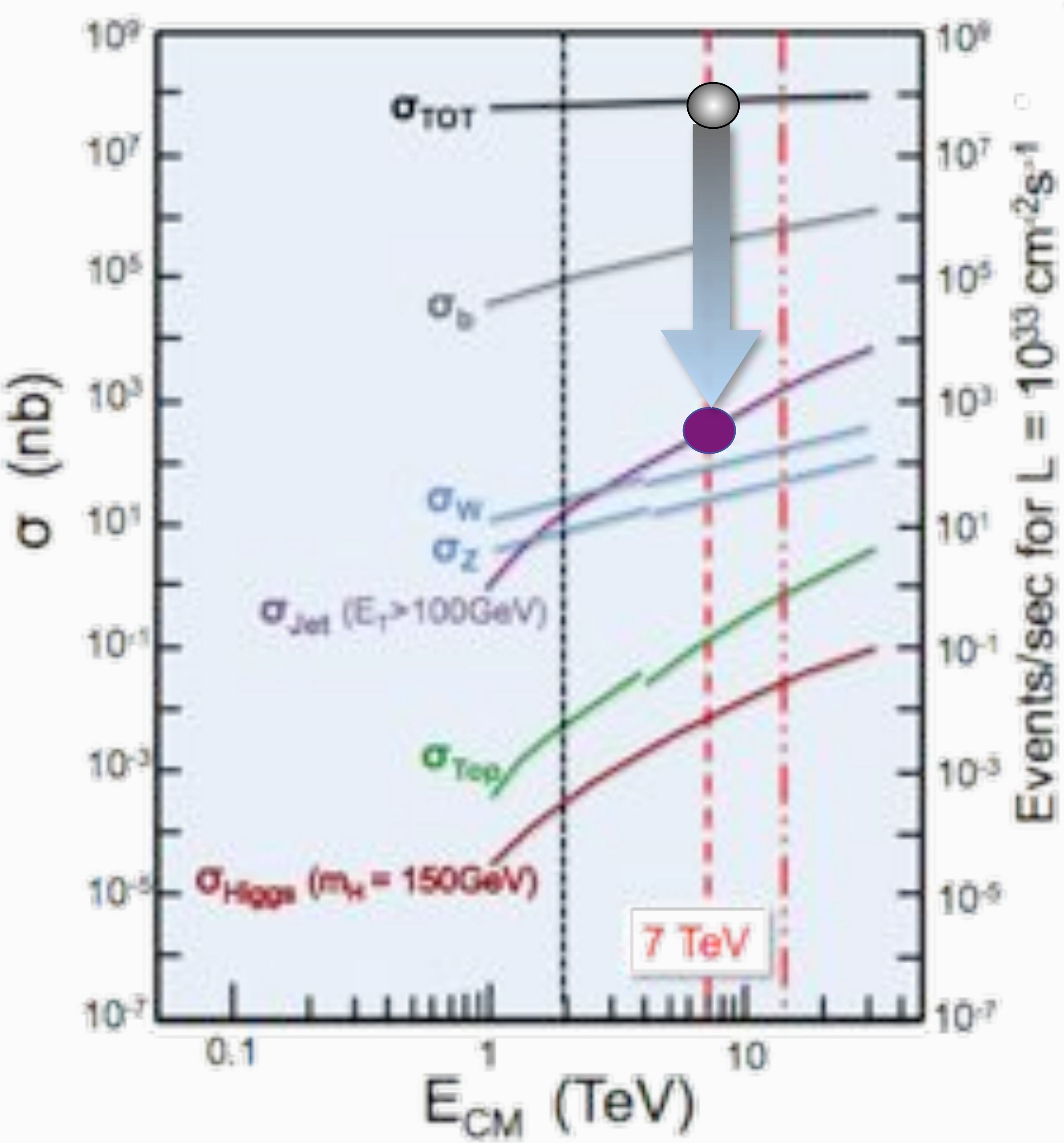
- Inelastic low-p_T pp collisions
  - Most processes are due to soft and semi-soft interactions between incoming protons
    - particles in the final state have large longitudinal, but small transverse momentum -> small momentum transfer:
      - several hundreds of MeV



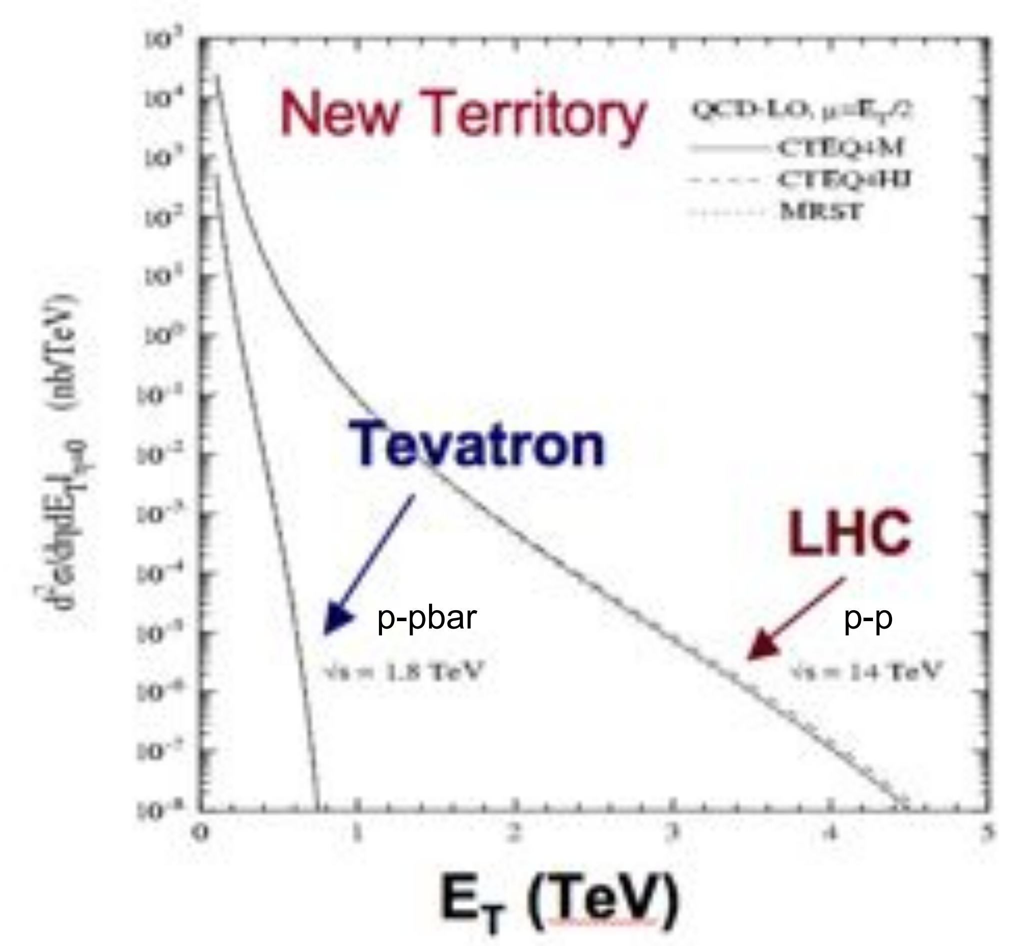
Low-p_T inelastic pp-collisions:
"Minimum Bias events"
Parameters (multiplicity etc) poorly known!
Important for tuning MC simulations,
and understanding of Pile-Up effects

- particle density:
  ~ 4 - 6 charged particles (pions) plus ~ 2 - 3 neutrals (π^0) per unit of pseudorapidity
  in the central detector region (and ~flat in rap)
- uniformly distributed in φ
- average p_T ~ few hundreds of MeV

Expected Physics : 2



- Measure Jet cross sections
  - E_T^{Jet} > 500 GeV after a few months at startup
  - Going fast beyond the TEVATRON reach
    - early sensitivity to compositiness



- requires good understanding of jets (algorithms, production, jet energy scale), PDFs, pile-up, underlying event, ...
- Thus : good calorimetry!!

Expected Physics : 3

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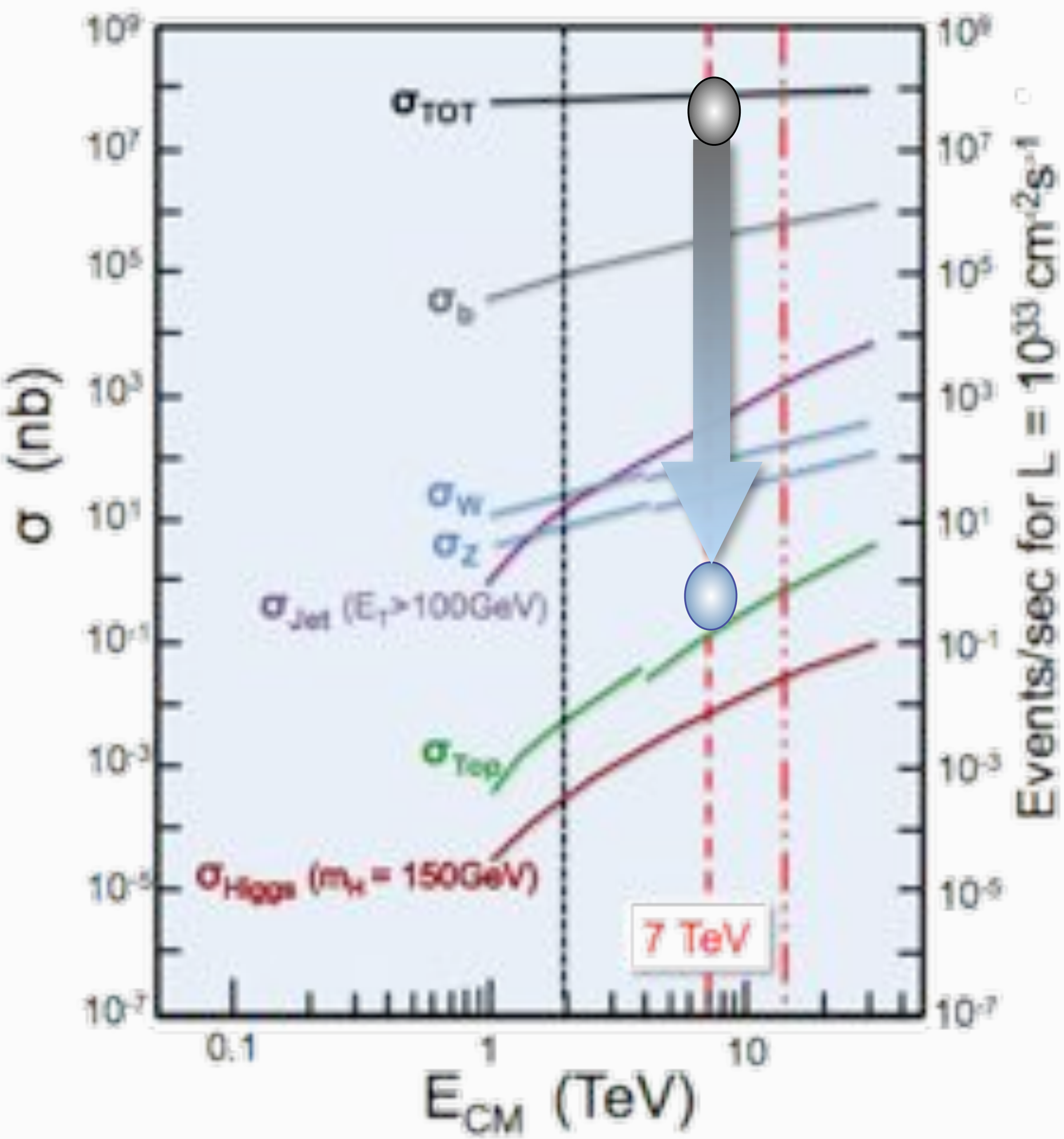


The Electroweak Sector

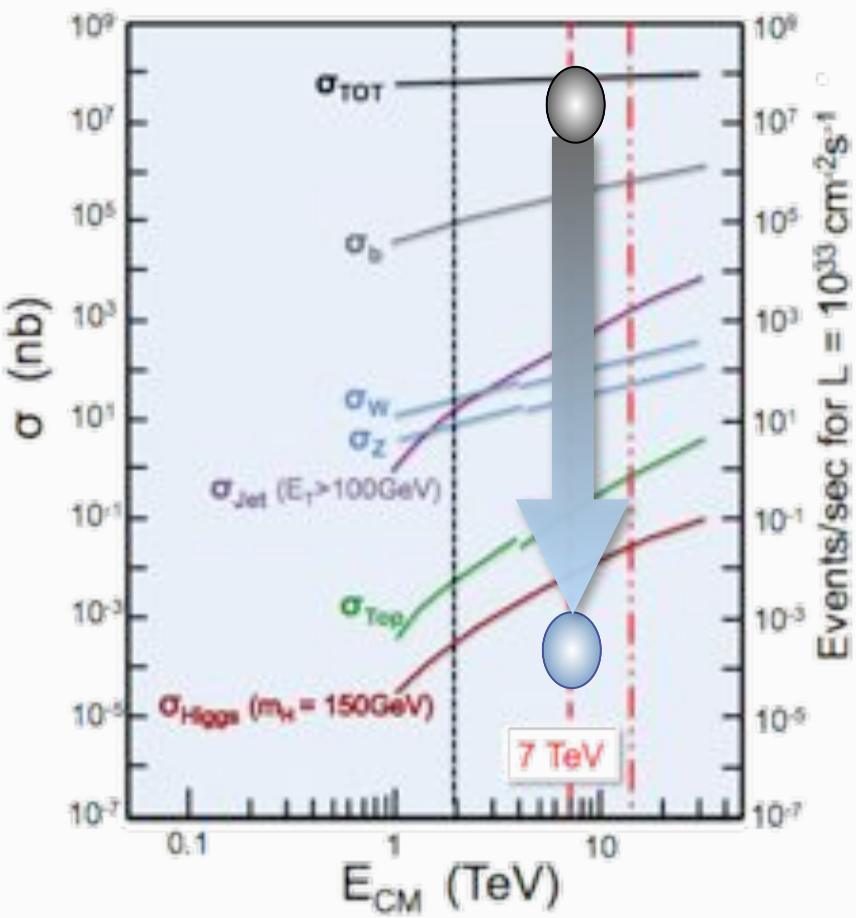
- test (re-establish the SM) and then go beyond
- most SM cross sections are significantly higher than at the TEVATRON
  - eg. 100x larger top-pair production cross section
  - the LHC is a top, b, W, Z, ..., Higgs, ... factory

Important:
Concentrate on final states with high-p_T and isolated **leptons and photons** (+ jets)

Otherwise overwhelmed by QCD jet background!!

Benchmarks

- Some benchmark processes of the early days, which influenced certain design parameters:
  - Basic processes relevant for studying electro-weak symmetry breaking (as seen in early days):



$$p\,p \rightarrow W^+ W^- \rightarrow \mu^+ \nu_\mu\, \mu^- \bar{\nu}_\mu$$

$$p\,p \rightarrow H \rightarrow ZZ \rightarrow \mu^+ \mu^- \mu^+ \mu^-$$

$$p\,p \rightarrow H \rightarrow ZZ \rightarrow \mu^+ \mu^- \nu_\mu \bar{\nu}_\mu$$

$$p\,p \rightarrow H \rightarrow \gamma\gamma$$

$$p\,p \rightarrow H \text{ jet jet } \text{(VBF)}$$

$$p\,p \rightarrow Z' \rightarrow \mu^+ \mu^-$$

  - All cross sections (times BR) of order 1 - 100 fb : determines needed luminosities for sizable statistics

So, some numbers to remember

- For some nominal numbers, eg. a bunch spacing of 25 ns:
  - relevant cross sections for testing of EWK symmetry breaking of order 1 - 100 fb^{-1}
  - Running time per year T ~ 10^7 secs (don't forget efficiency factors....)

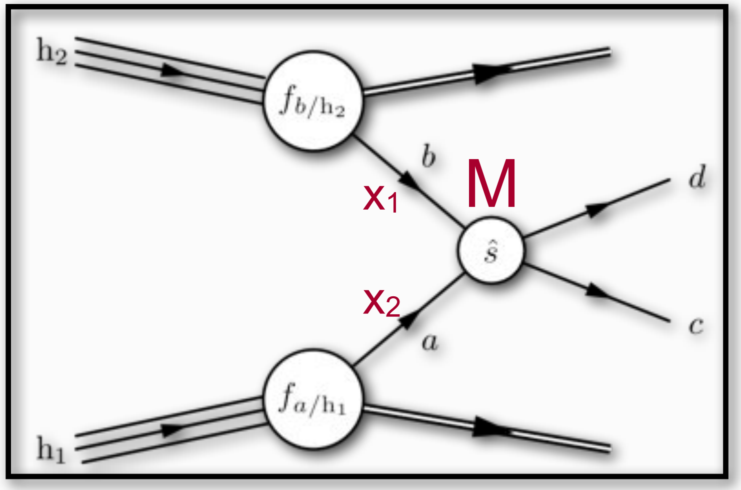
$$\text{for } \mathcal{L} = 10^{34}/\text{cm}/\text{sec} = 10^{-5}\,\text{fb}^{-1}/\text{sec}$$

$$N = (\mathcal{L}\cdot T)\,\sigma \Rightarrow 100\,\text{events per year for } \sigma = 1\,\text{fb}$$

  - Total rate of inelastic events $R = \sigma_{\text{inel}}\,\mathcal{L} \approx (100\,\text{mb})\,(10^7\text{mb}^{-1}/\text{sec}) = 10^9\,\text{events}/\text{sec}$
  - Number of inelast. events per bunch crossing = 10^9/sec * 25 10^{-9} sec = 25 (pile-up)!
  - Number of chg. particles per bunch x-ing : 25 * N(pions)/rap * (2 y_{max}) ~ 2000 !!
  - Thus have an issue with **radiation levels**! (and pile up ...)

Production of heavy states

- Heavy particles are produced "more centrally"
  - example: single heavy resonance (eg. Z') of mass M, Energy E, rapidity y :

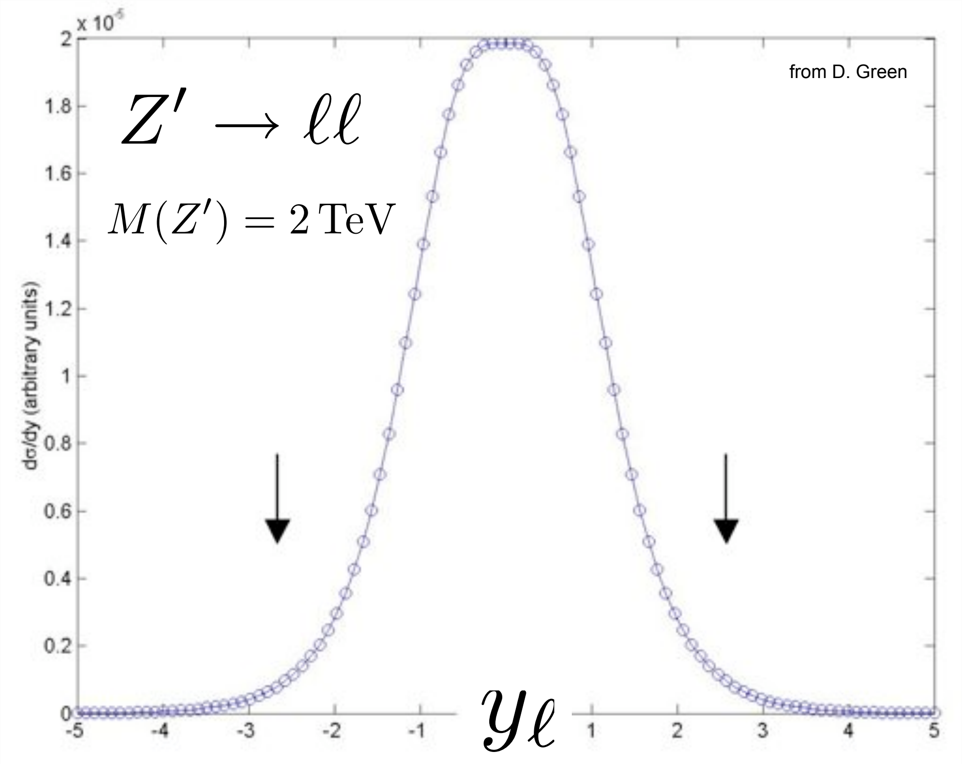


$$\hat{s} = x_1\, x_2\, s = M^2 \qquad x_1 \approx x_2 \to x_{1,2} = \frac{M}{\sqrt{s}}$$

$$E = \frac{\sqrt{s}}{2}(x_1 + x_2) \qquad p_L = \frac{\sqrt{s}}{2}(x_1 - x_2)$$

$$y = \frac{1}{2}\ln\frac{E + p_L}{E - p_L} \Rightarrow e^y = \sqrt{\frac{x_1}{x_2}} \Rightarrow y \to 0 \text{ for } x_1 \approx x_2$$

$$x_{1,2} = \frac{M}{\sqrt{s}}\, e^{\pm y}$$



- Thus important to concentrate on precision tracking/calorimetry in area of approx. $|y| < 2.5$

Examples of detector performance requirements

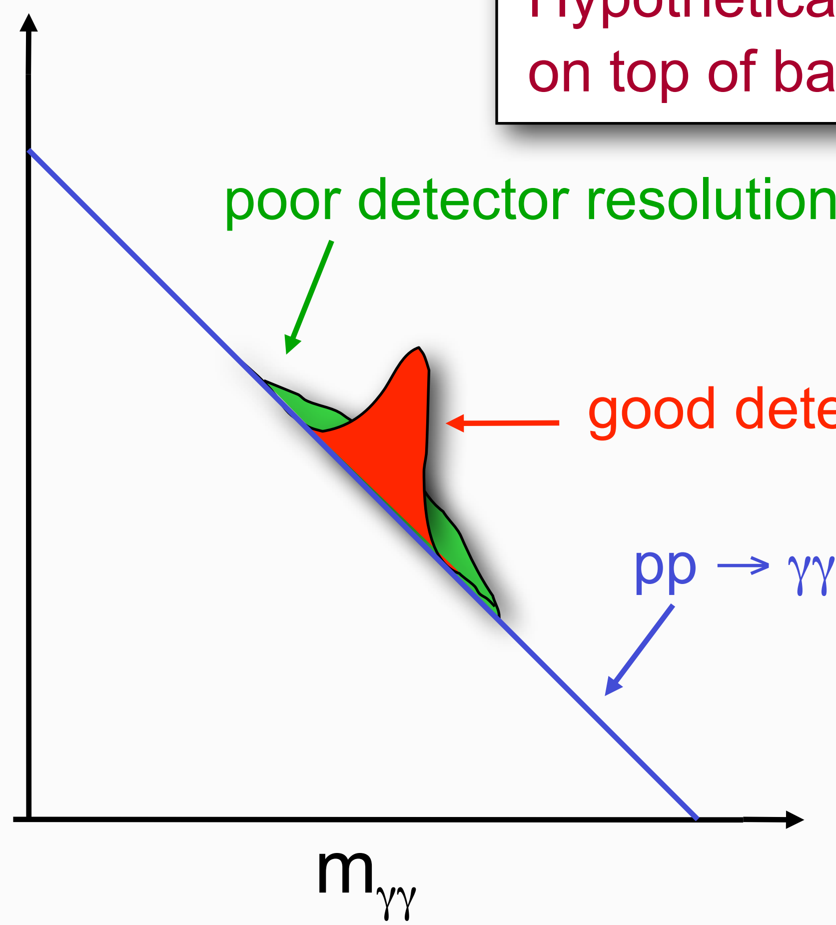
Lepton measurement: $p_T \approx$ GeV $\rightarrow$ a few TeV ($b \rightarrow l+X$, W/Z, W'/Z', …)

Mass resolutions:

≈ 1% decays into leptons or photons
(Higgs, new resonances)

≈ 10% $W \rightarrow jj$, $H \rightarrow bb$
(top physics, Higgs, …)

Hypothetical $X \rightarrow \gamma\gamma$ signal on top of background



Particle identification:

- b/jet separation : ε (b) ≈ 50% R (jet) ≈ 100 (H → bb, SUSY, 3rd generation !!)
- τ/jet separation : ε (τ) ≈ 50% R(jet) ≈ 100 (A/H → ττ, SUSY, 3rd generation !!)
- γ/jet separation : ε (γ) ≈ 80% R(jet) > 10^3 (H → γγ)
- e/jet separation : ε (e) > 70% R(jet) > 10^5 (inclusive electron sample)

Tools and Methods

Our Master Equation

ETH Institute for Particle Physics

Event rates (absolute, relative, differential)
Stat vs syst errors, backgrounds from data or MC?
Resolution, Energy Scale, Signal Significance

$$\sigma_{\mathrm{meas}} = \frac{N_{\mathrm{obs}} - N_{\mathrm{bkg}}}{\varepsilon \quad L}$$

Proton-Proton Luminosity uncertainty < 5%

Experimental issues : Triggers, reconstruction, isolation cuts, low-p_T jets (jet veto) acceptance, efficiency determination (tag&probe)

Theoretical issues : p_T distributions at NLO + resummation; differential calculations for detectable acceptance.

$$\sigma_{\mathrm{theo}} = PDF(x_1, x_2, Q^2) \otimes \hat{\sigma}_{\mathrm{hard}}$$

constrain, define uncertainties

HO calculations, implement in MC

Goal : test SM (in)consistency : $\sigma_{\mathrm{exp}} \pm \Delta_{\mathrm{exp}} \stackrel{?}{=} \sigma_{\mathrm{SM}} \pm \Delta_{\mathrm{th}}$

Efficiencies and Acceptance

$$\sigma_{\text{meas}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\varepsilon L}$$

Efficiencies and acceptances

$$\sigma_{\text{meas}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\varepsilon \ L}$$

$$= \epsilon_{\text{ID}} \cdot \epsilon_{\text{RECO}} \cdot \epsilon_{\text{TRIG}} \cdot A$$

Identification eff.

Number of "reconstructed" objects/events, which have passed the ID criteria
———
Number of "all reconstructed" objects/events

Trigger eff.

Number of "detectable" objects/events, which have been triggered on
———
Number of "all detectable" objects/events

Acceptance

Number of "detectable" objects/events
———
Number of "all produced" objects/events

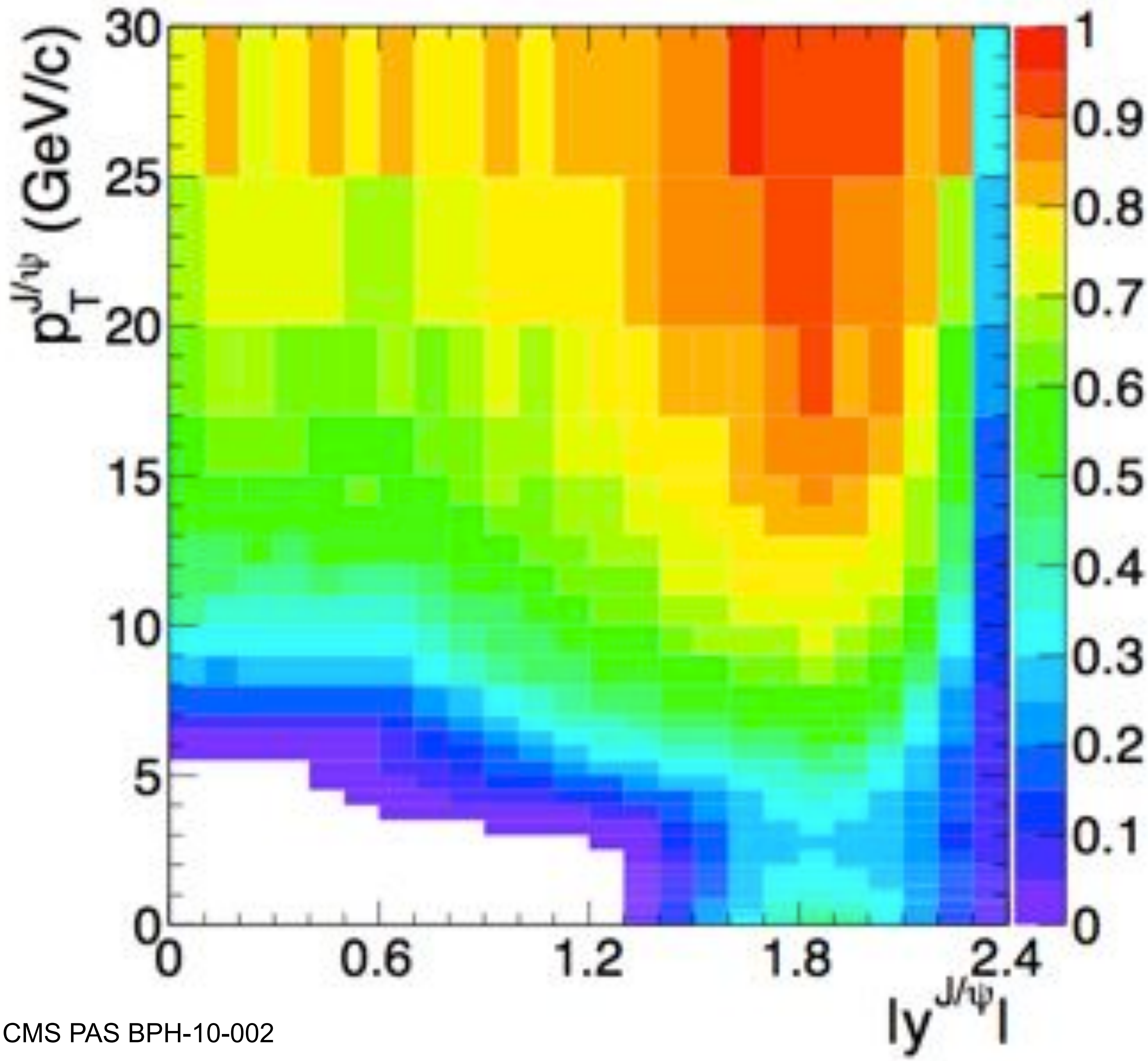
Reconstruction eff.

Number of "detectable, triggered" objects/events, which have been reconstructed
———
Number of "detectable/triggered" objects/events

example, from MC:

N(muons) with p_T > 10 GeV and eta<2
———
N(all generated muons)

Acceptance, Example

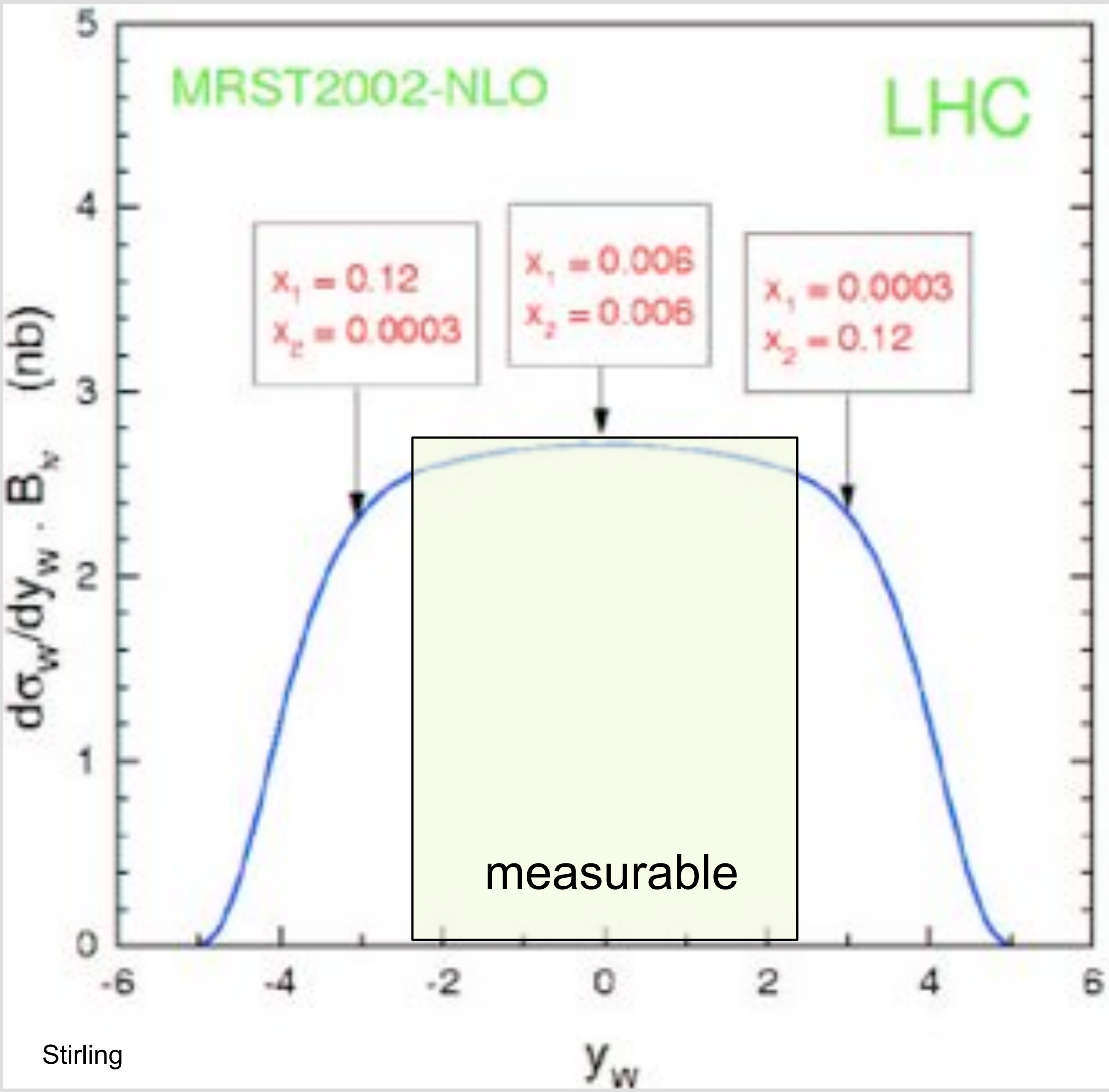


CMS PAS BPH-10-002

- A “tricky” case:
  - Acceptance for J/Psi, in CMS at 7 TeV
  - as a function of the p_T and rapidity of the J/Psi
  - this is a convolution of the acceptances for the two muons, coming from the J/Psi decay
  - Muon acceptance strongly determined by detector geometry and magnetic field, as well as muon penetration power (iron thickness vs. momentum)

Issue of acceptance...

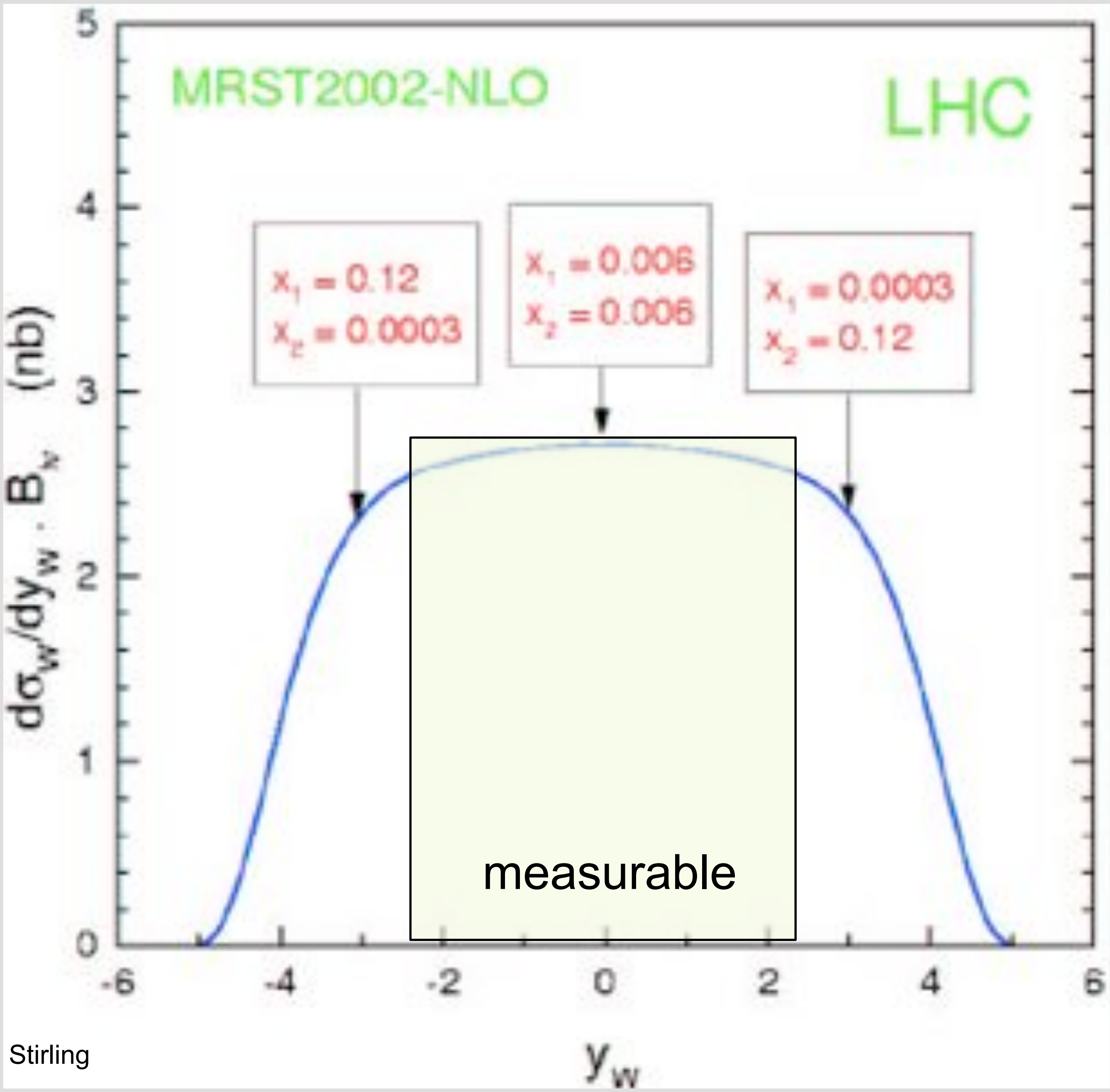
- Example: W or Z production



- Again, is a convolution of the acceptances for the leptons
- **Do we really want to correct for acceptance?**
- **Pros:**
  - The cross section measurement can be directly compared to other (corrected) measurements, from other exps
  - The measurement can be compared to theory predictions which cannot be obtained for arbitrary acceptance
- **Cons:**
  - The measurement becomes model dependent
  - we introduce a systematic error, eg. because of uncertain extrapolation to full acceptance

Issue of acceptance...

- Example: W or Z production



if we want **precise measurement** of Luminosity or some parameter in hard-interaction cross section, it is essential to have HO calc.

restricted to measurable acceptance

⇒ avoid **extrapolation errors**

eg. from extrapolation to large y_W where uncertainties from pdfs are large!

... fortunately, nowadays more and more fully differential calculations are available.... thus it becomes possible to calculate "EXACTLY" what is measured....

Trigger efficiencies

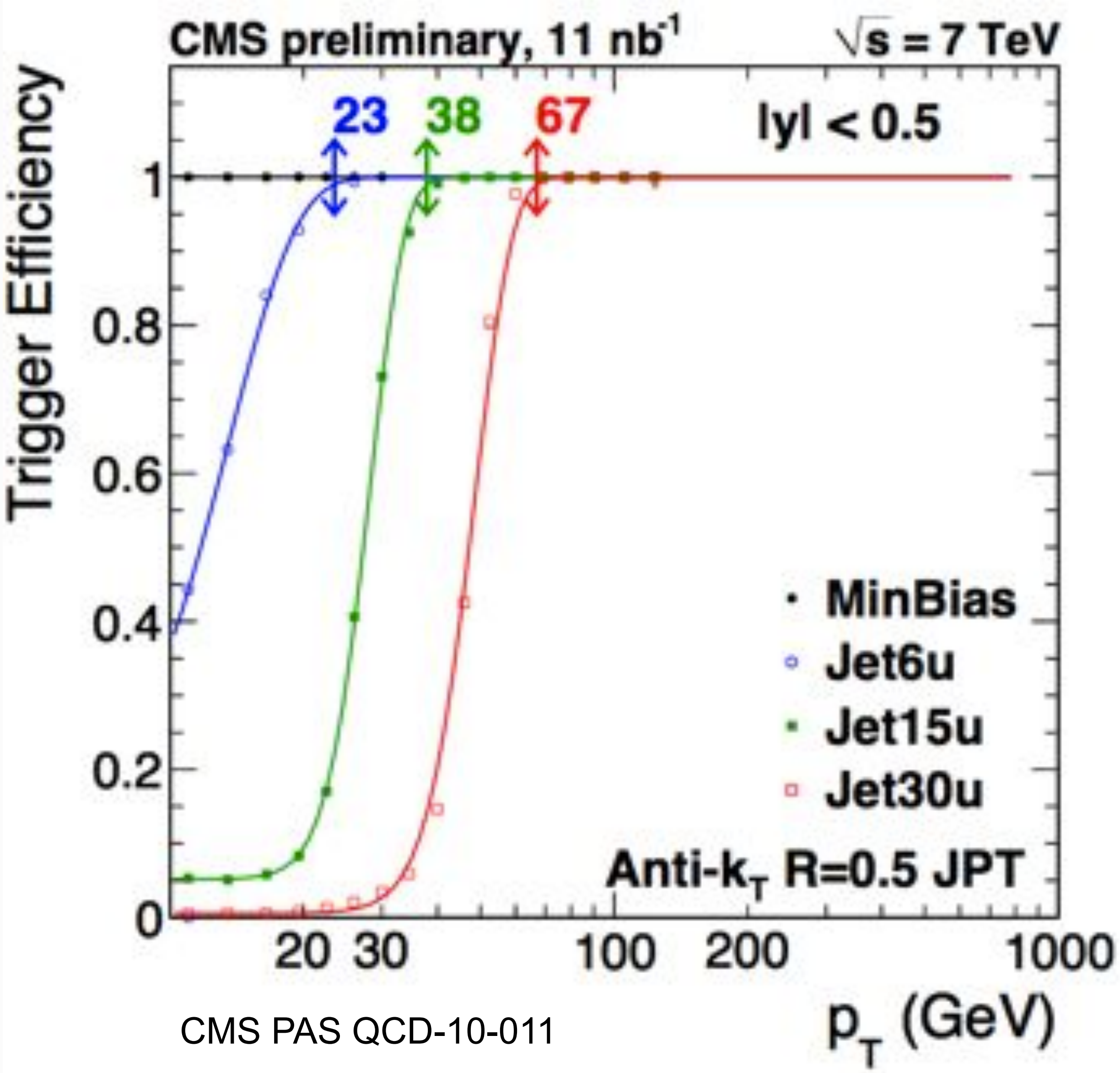
- **Usual recipe**: try to have a "more inclusive" trigger, where you "know" that it is "100% efficient", and calculate rate w.r.t. this one
- Example: trigger rate for a Jet Trigger with E_T>15 GeV:

$$\epsilon_{TRIG} = \frac{N(\text{ Jet15 Trigger AND MinBias Trigger })}{N(\text{ MinBias Trigger })}$$

- **Minimum Bias Trigger**: a minimal set of selection criteria are applied, eg. a few hits in the beam scintillation counters
- compare, eg. to **Zero Bias Trigger**

- Then, the efficiency of a higher Jet ET trigger, eg. 30 GeV, can be found from:

$$\epsilon_{TRIG} = \frac{N(\text{ Jet30 Trigger AND Jet15 Trigger })}{N(\text{ Jet15 Trigger })}$$



CMS PAS QCD-10-011

- Typically, apply selection cuts only above a p_T where your trigger is >99% efficient!

The Tag & Probe Method

- Useful to measure efficiencies from data
  - trigger eff, reconstruction eff., identification eff.
  - eg. single muon trigger eff.: what is the fraction of reconstructed muons, which would also have been triggered on?
  - eg. electron ID eff: what is the fraction of reconstructed electron candidates, which also pass a tight isolation criterium?

$$\epsilon_{ID} = \frac{\text{N(Probes which pass further criteria)}}{\text{N(all tags)}}$$

Probe Object: “loosely” selected:

now apply further criteria

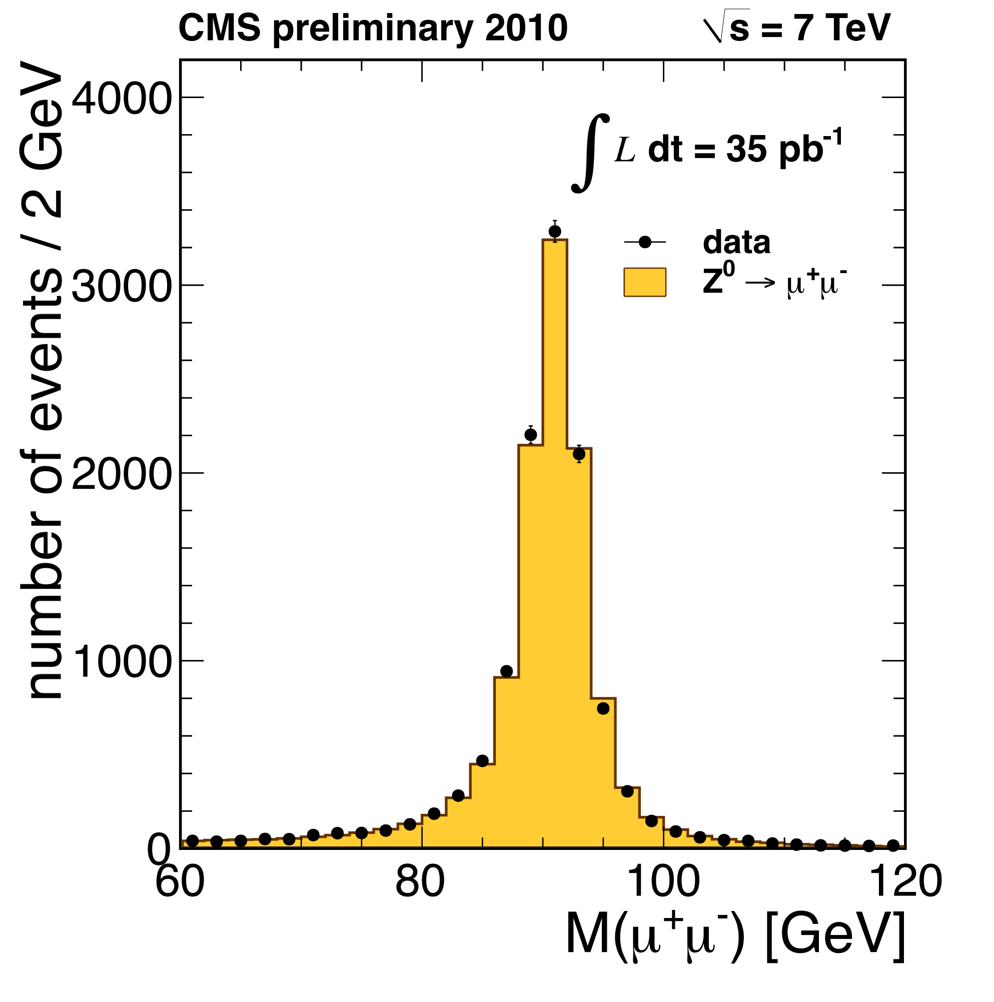
Tag Criterium: eg. di-lepton system close to invariant mass of Z or J/Psi; or a very pure W candidate: one isolated lepton, large MET, no further activity in the event, transverse mass > X

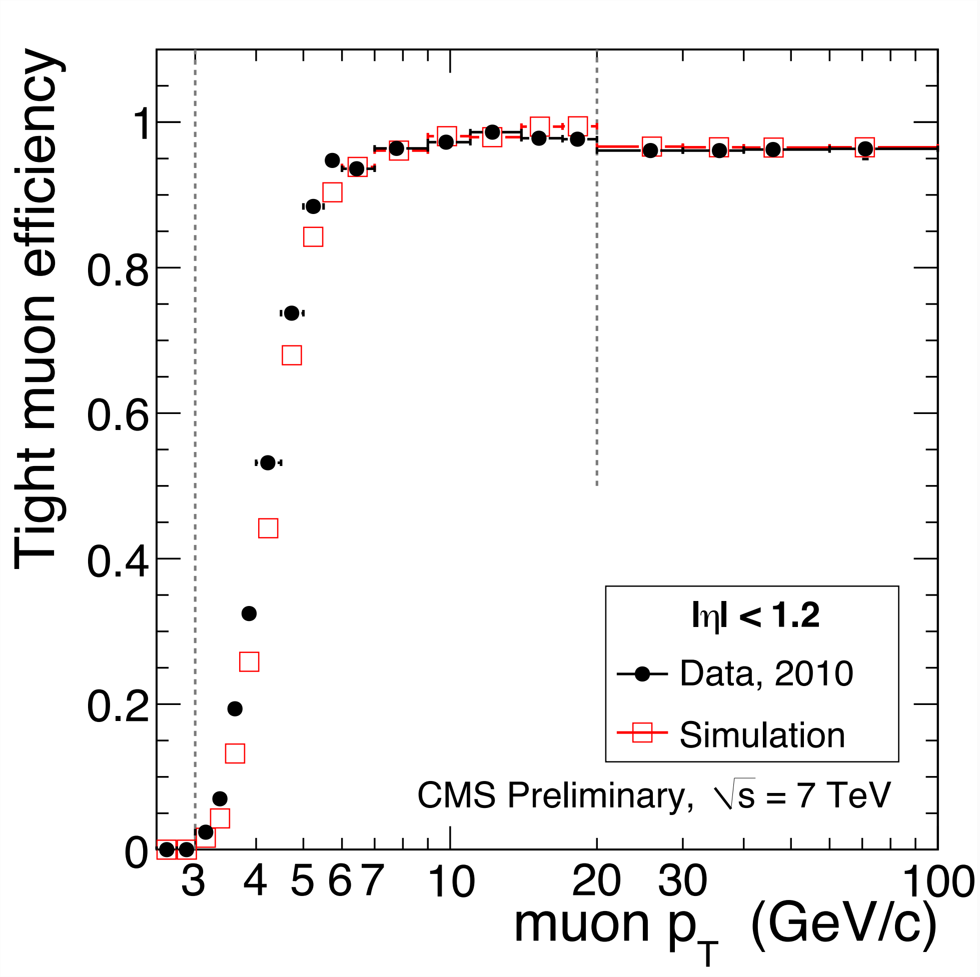
Tag Object: “tight” selection applied:

defined the tag together with the additional criterium above

Tag & Probe....

- **Careful**:
  - make sure no background left, or subtract it
  - make sure no correlations introduced
- Apply same method in data and MC.
  In MC: compare to “True Eff.” and if necessary apply (hopefully small) additional correction factors, if some bias is observed





see eg. https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsMUO

Backgrounds

$$\sigma_{\text{meas}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\varepsilon \quad L}$$

see also later some applications......

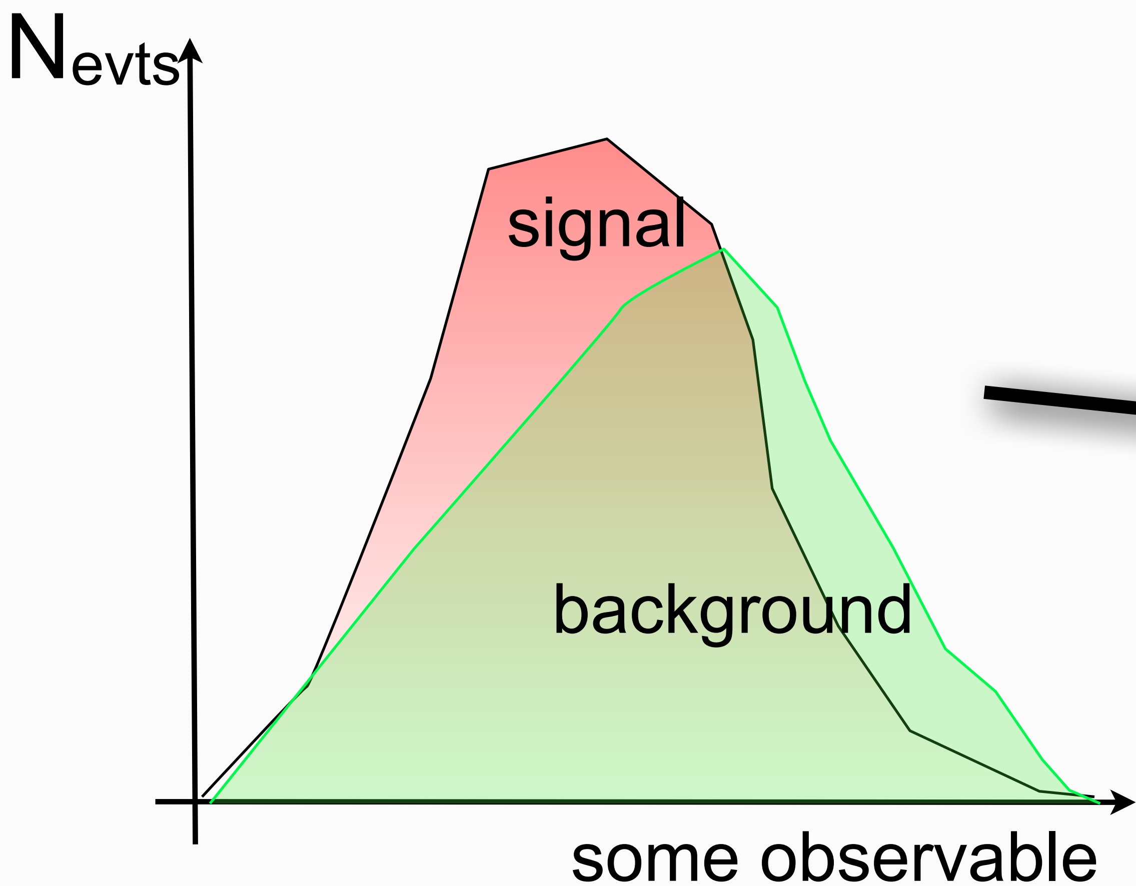
General observations

$$\sigma_{\text{meas}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\varepsilon \; L}$$

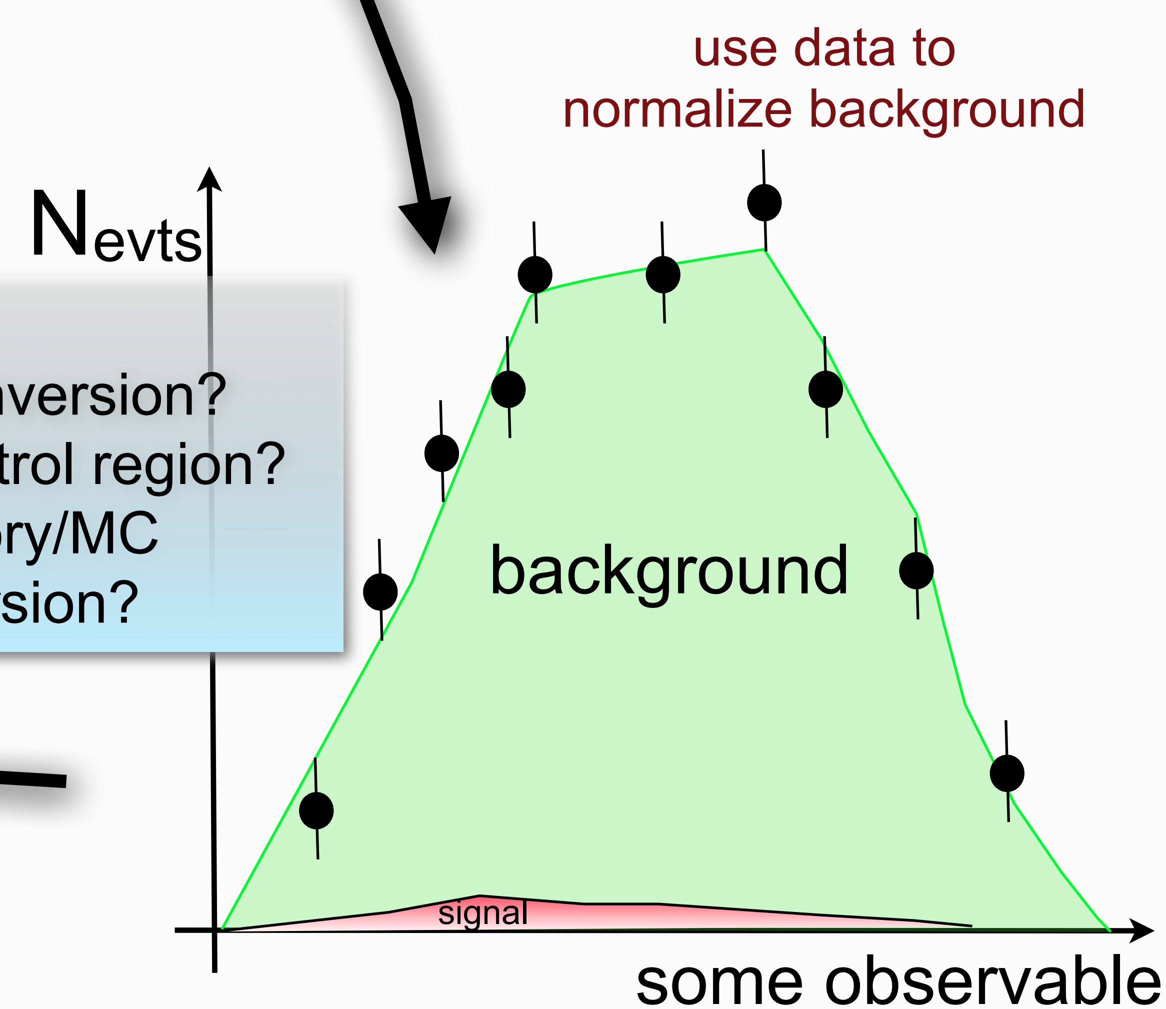
- Apply selection which optimizes
  - either: sum of stat + syst error
  - or : best S/B S=N(**S**ignal), B=N(**B**ackground
  - or : best S/sqrt(B) or : .....
- How to find optimum, especially if S/B <<1, complicated signatures, many variables involved?
  - modern approach : "Multi-Variate Approaches"
- If you have
  - **S/B >> 1** : don't have to worry much about syst. uncertainty of B, in case of searches it won't affect much the significance or your signal or your exclusion limit
  - **S/B < 1** : you should worry!

Data-Driven Background Estimates

the general idea



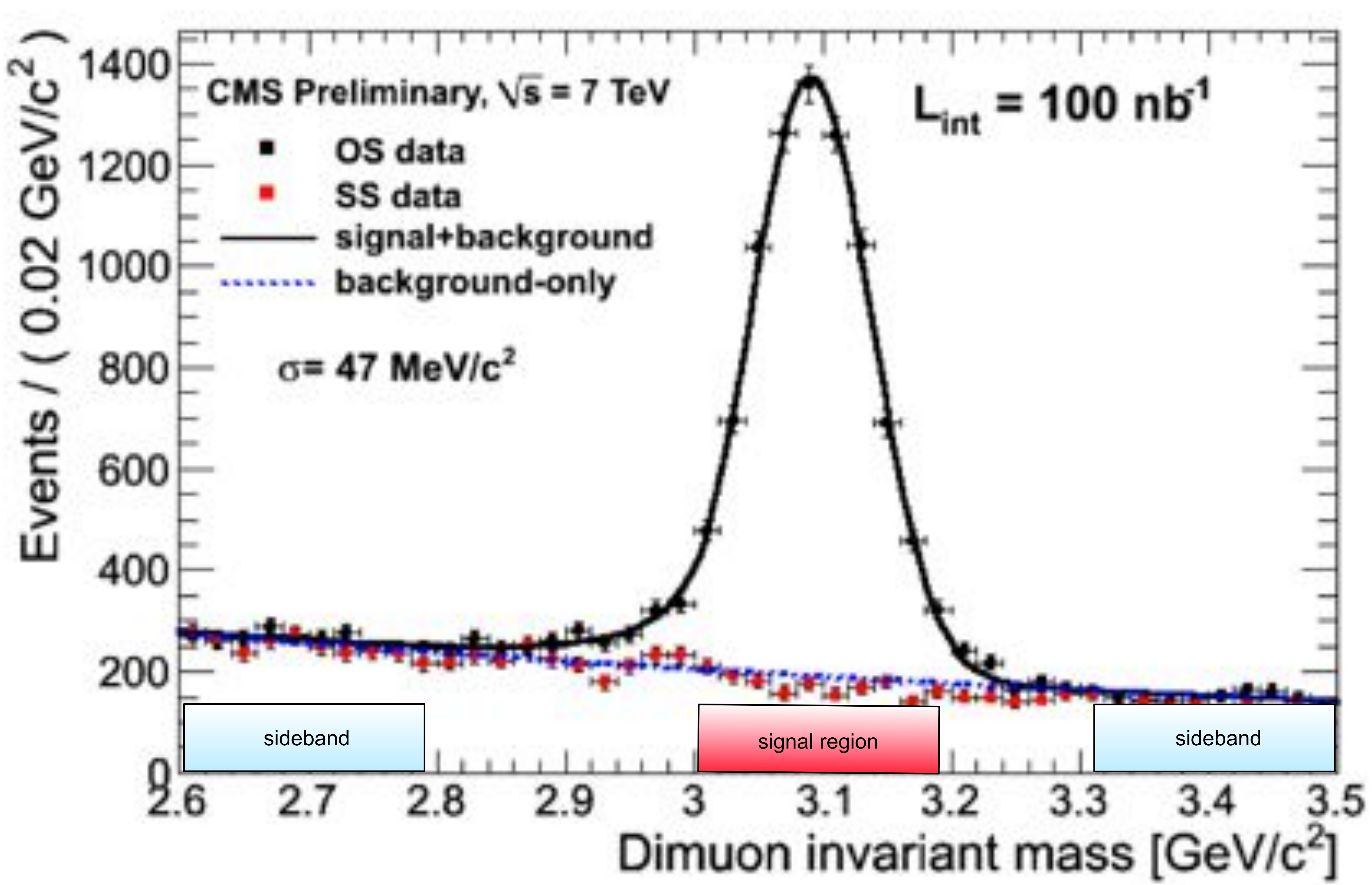
invert cuts :
from signal enhancement to background enhancement



Issues:
- is signal left after inversion?
- any bias in the control region?
- how well does theory/MC model the cut inversion?

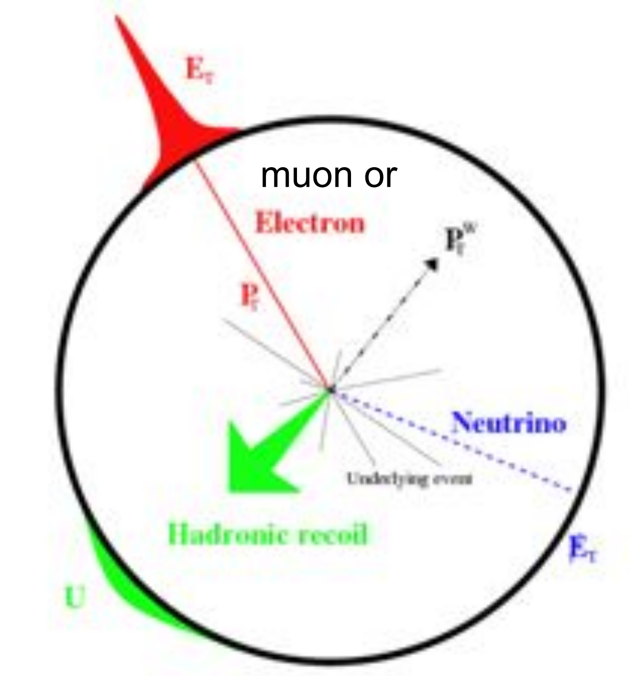
going back:
use theory (MC) to compute change in background when inverting cuts; or use some well-motivated extrapolation, data only

The “trivial” case : Sidebands



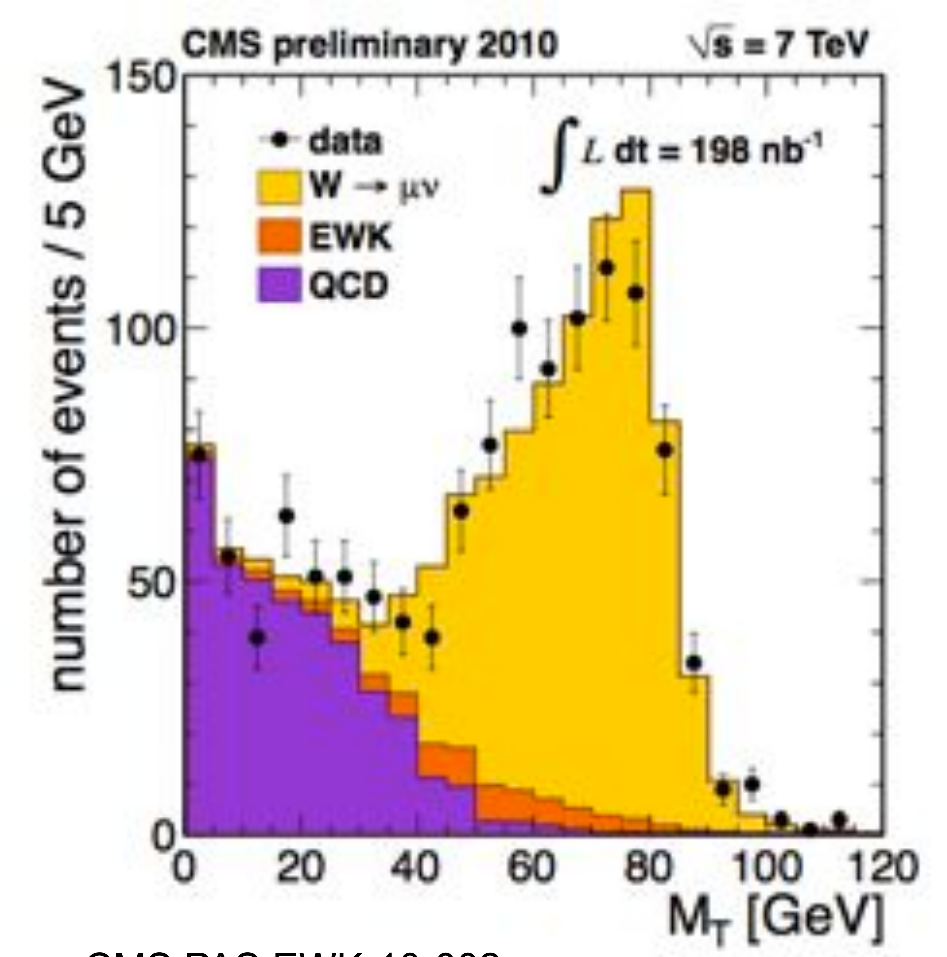
CMS PAS BPH-10-002

A less trivial case : W selection



W: decay to charged leptons
- high-p_T
- isolated
- $E_{T,miss}$ (from neutrino)

transverse mass: $M_T = \sqrt{2 p_T(\mu) \not{E}_T (1 - \cos(\Delta\phi_{\mu,\not{E}_T}))}$



CMS PAS EWK-10-002

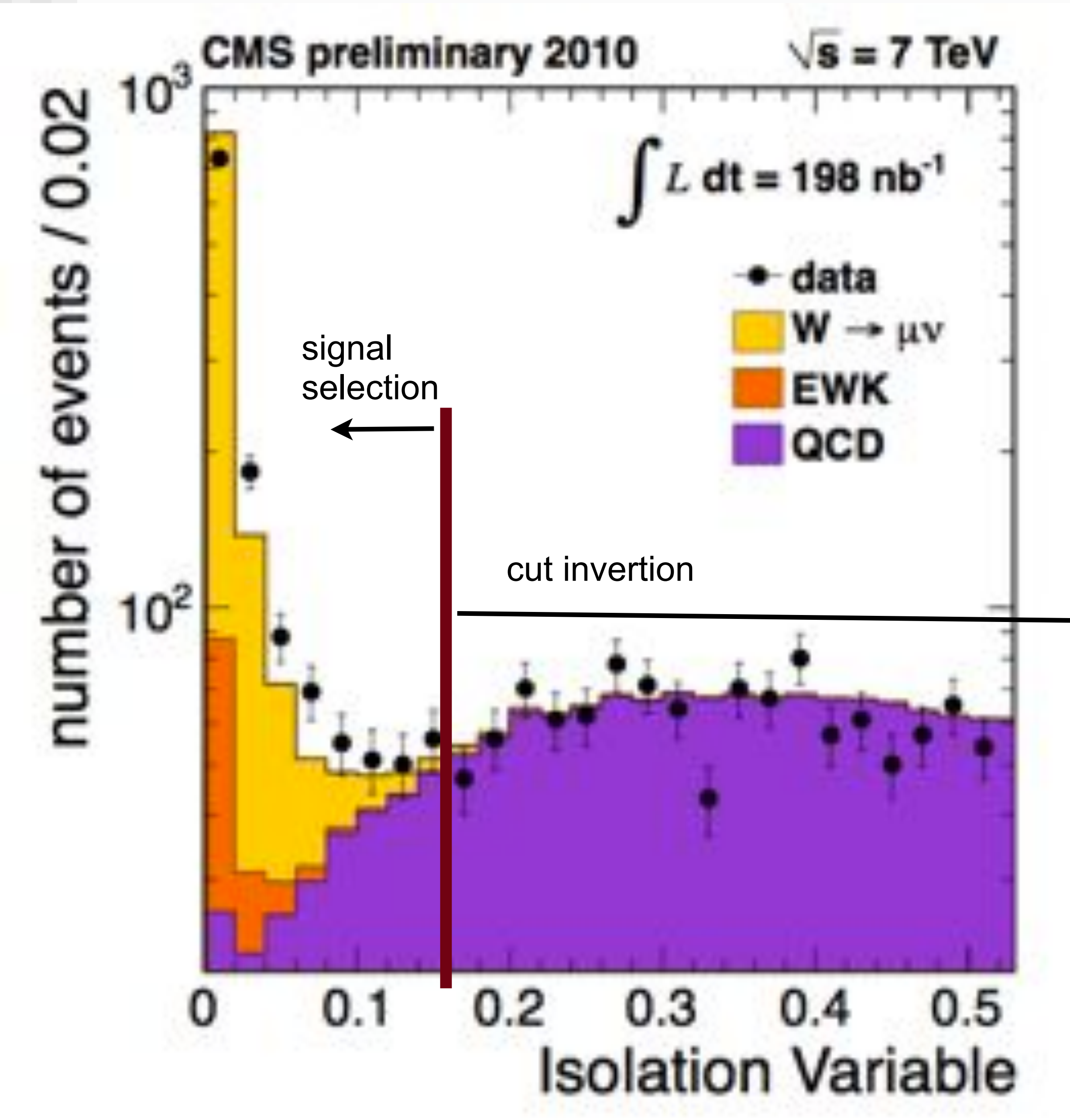
after cut on important selection variable, the relative isolation:

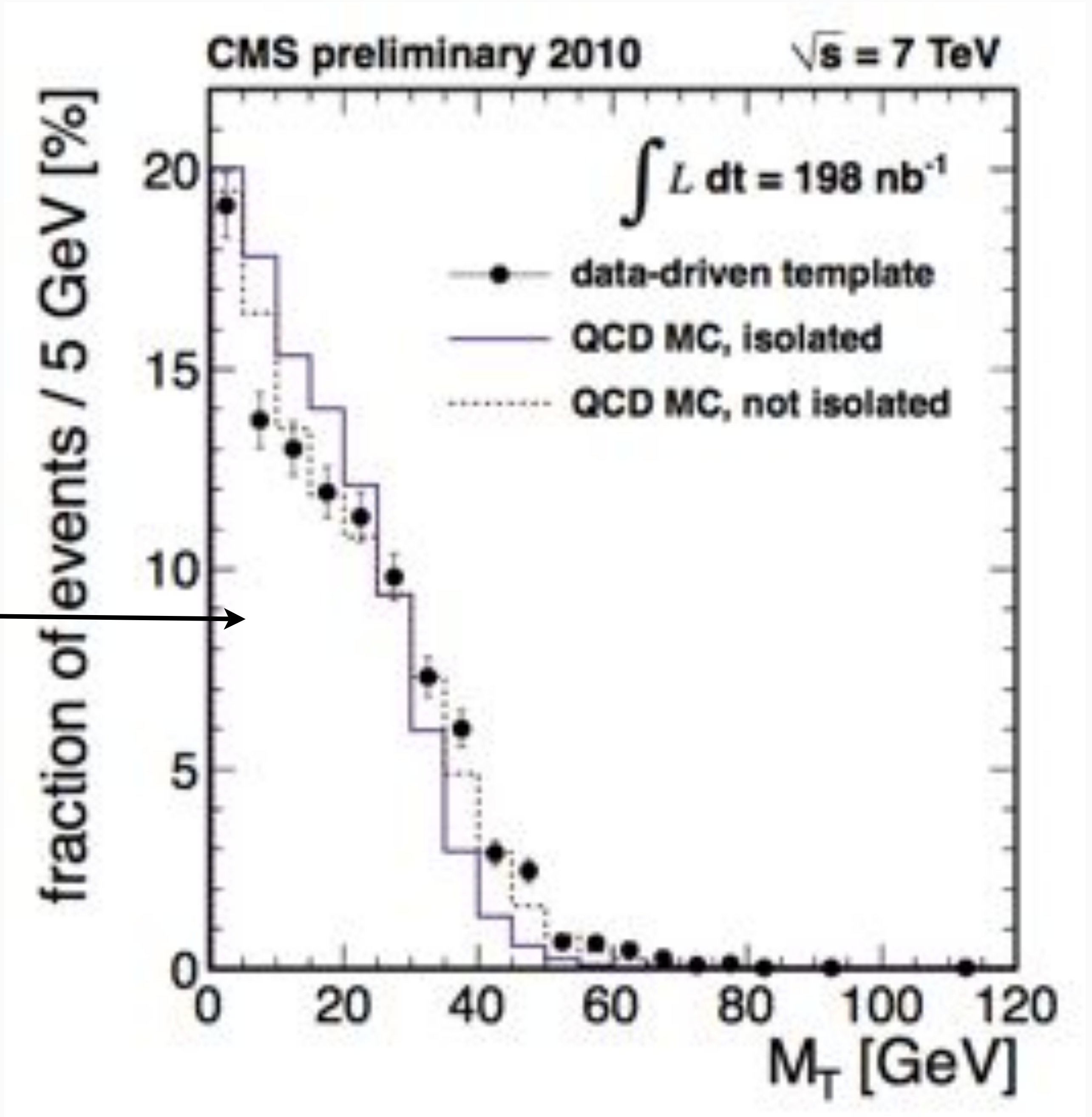
$$I^{rel}_{comb} = \left\{ \sum (p_T(tracks) + E_T(em) + E_T(had)) \right\} / p_T(\mu)$$

in cone $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.3$ around the muon

A less trivial case : W selection

CMS PAS EWK-10-002





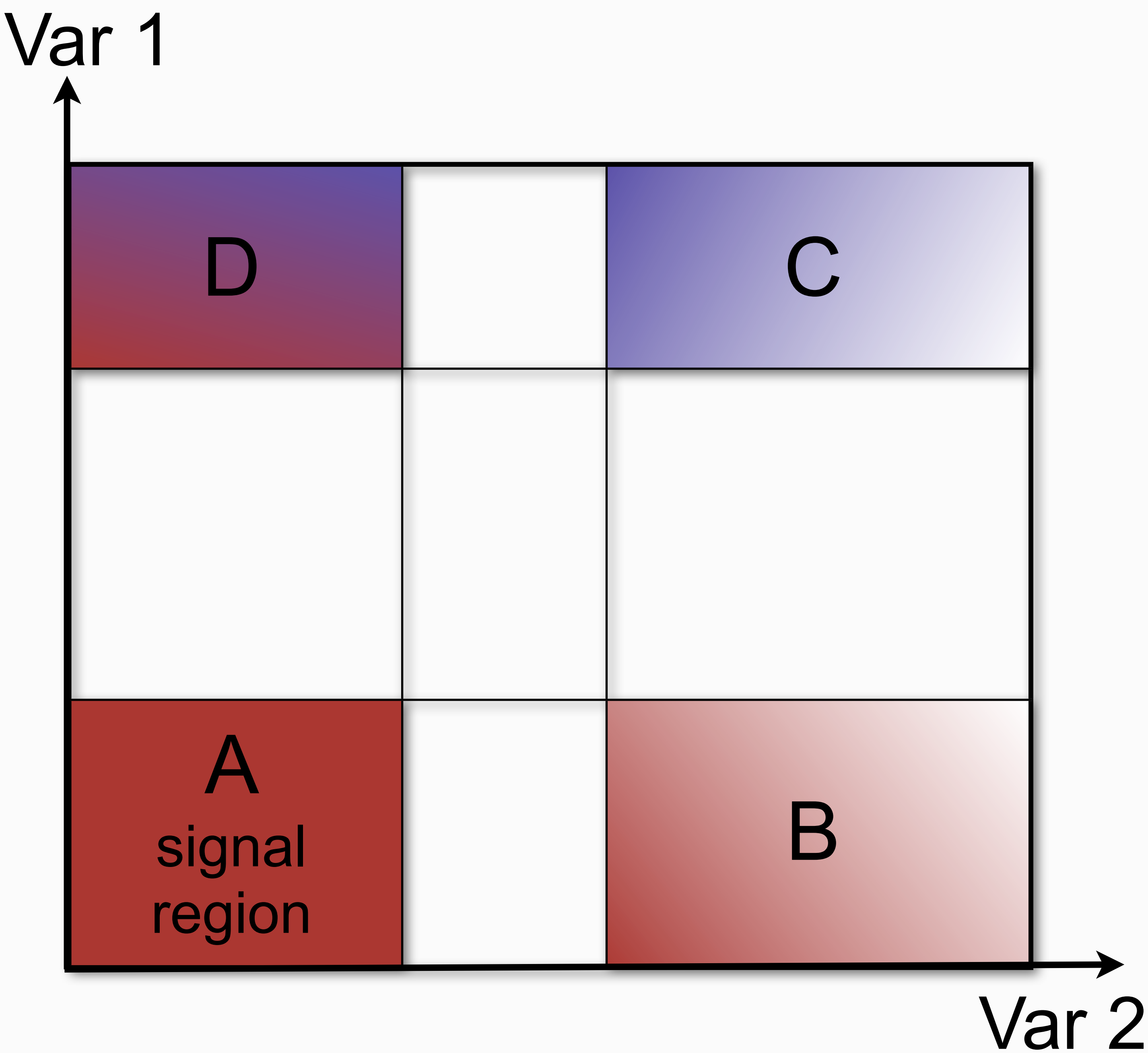
$p_T > 20$ GeV/c in $|\eta| < 2.1$

QCD bkg: mostly b-decays

take this shape for fit to M_T distribution

The "ABCD" method

- find two variables, which characterize the events of interest
- A=signal region, B,C,D: background regions
- hypothesis of **un-correlated** variables:
  background shape in AD sector is the same as in BC sector



If this hypothesis is true, and **no** signal contamination in B,C,D:

estimate for background in signal region is

$$\frac{N(A)}{N(D)} = \frac{N(B)}{N(C)} \Rightarrow N(A)$$

from the counted number of events N(B,C,D) in the background regions.

Fake rates

- What is probability that eg. a jet is mis-identified as an "isolated" lepton?
  - Important to know for leptonic analyses, especially in case of search for rare "multi-lepton" signatures
  - even if tight isolation requirements are applied, the probability of faking is not zero, and a small number, multiplied with the huge cross section of multi-jet production, can still lead to a sizable background
  - difficult (impossible?) to trust the simulation on this faking probability, rather try to get it from data
- "Standard Method":
  "Fakeable Object method", or "Tight-To-Loose Ratio"
  - **Idea** : define two selection steps, one with **LOOSE** criteria, and one with **TIGHT** criteria (eg. on isolation)
  - determine the "**fake ratio**", or "probability for a jet to fake a lepton" from the ratio of tightly to loosely selected objects, in a control sample that should not have any prompt leptons (eg. multi-jet sample)
  - determine this number as function of basic kinematics (p_T, rapidity)
  - apply it to a MC background simulation, or at a preselection level, to determine this fake background on the final selection level

Fake ratio

- N_L = number of loosely selected objects
- N_p = number of prompt leptons,
- N_f = number of fake leptons
- N_{Tp} = Number of objects passing the tight selection
- N_{Tf} = Number of objects failing the tight selection
- p = probab. of prompt lepton to pass tight selection, typically ~ 1
- f = probab. of jet, to pass tight selection

$$N_L = N_p + N_f = N_{Tp} + N_{Tf}$$

$$N_{Tp} = p\, N_P + f\, N_f \approx N_p + f\, N_f$$

$$\rightarrow f = \frac{N_{Tp} - N_p}{N_f}$$

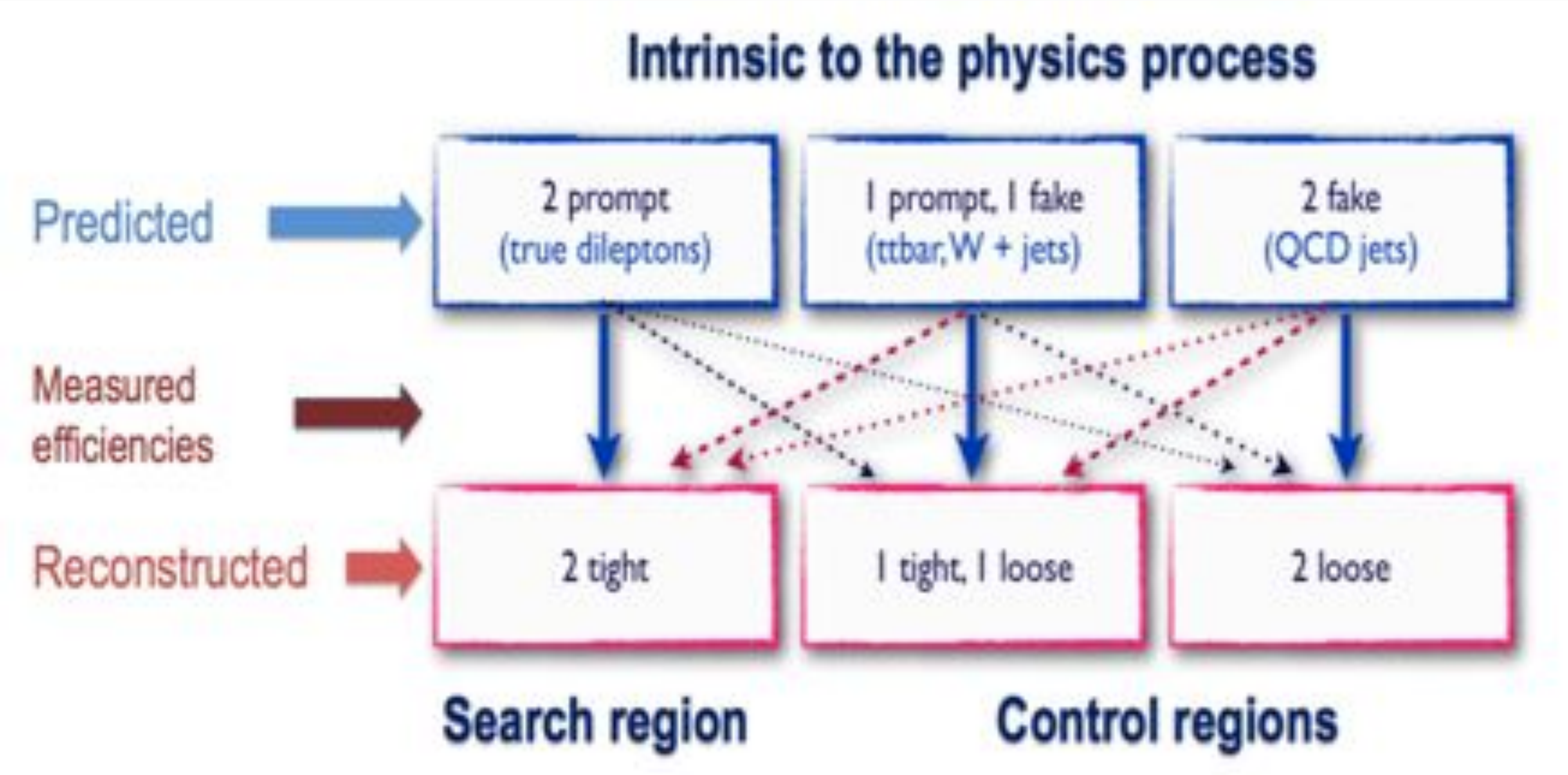
- on a control sample (pure background): (eg. jet-triggered sample)

$$N_p \rightarrow 0 \quad N_f = N_L - N_p \rightarrow N_L$$

$$\Rightarrow f = \frac{N_{Tp}}{N_L}$$

Fake ratio

- use MC to correct for remaining signal contamination in control sample, or for p<1
- Extendable to more than one lepton
- Example: di-lepton SUSY search



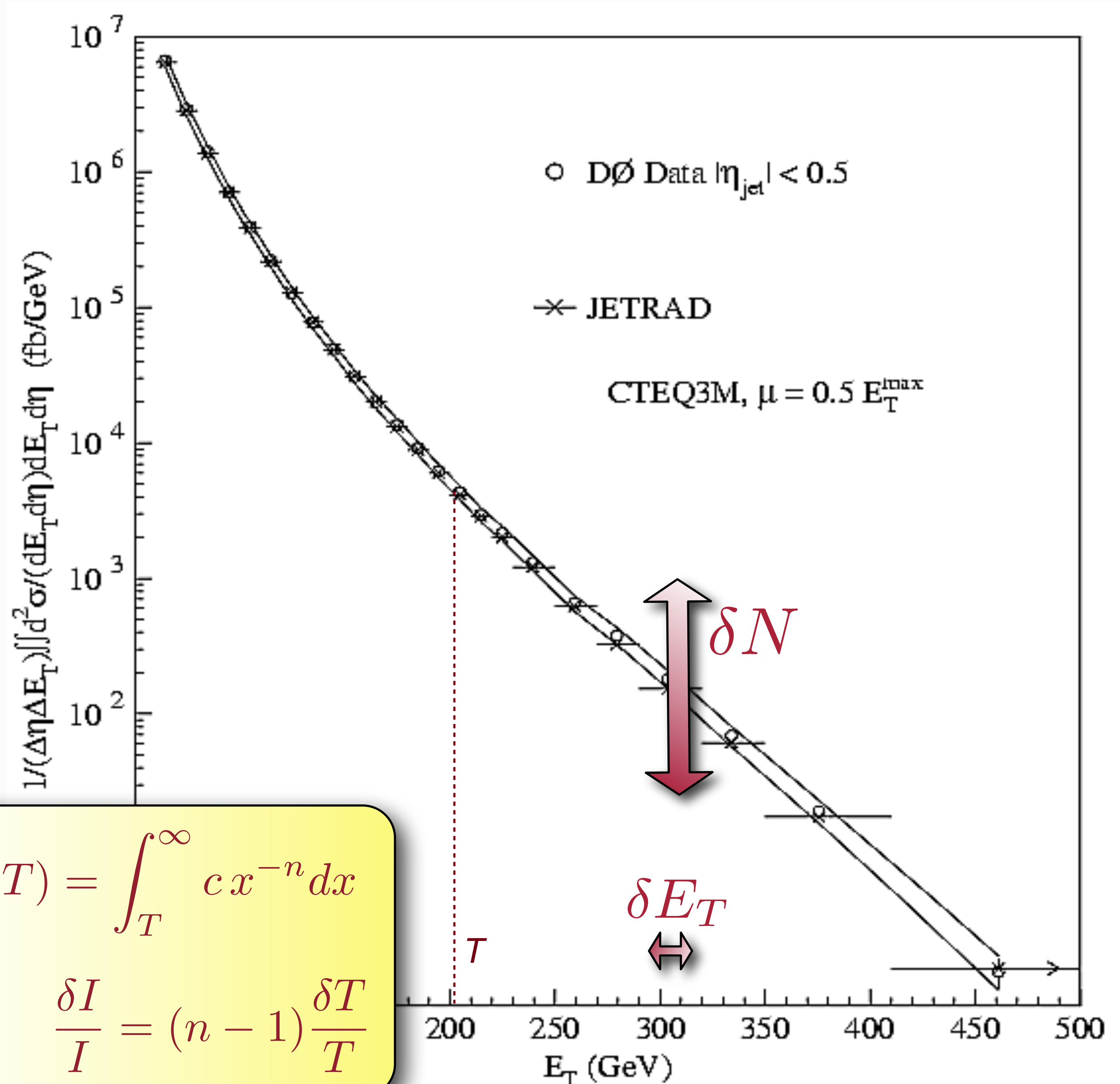
from PhD thesis, P. Milenovic

Issues when measuring steeply falling spectra

$$\sigma_{\mathrm{meas}} = \frac{N_{\mathrm{obs}} - N_{\mathrm{bkg}}}{\varepsilon \; L}$$

Problem 1 : Absolute scale

- Question : how well do we know the calibration of the variable on the x-axis, eg. jet energy?
- A general problem for a very steeply falling spectrum!



$$I(T) = \int_T^\infty c\, x^{-n} dx$$

$$\Rightarrow \quad \frac{\delta I}{I} = (n-1)\frac{\delta T}{T}$$

$$\frac{d^2\sigma}{dE_T d\eta} \approx \text{const} \cdot E_T{}^{-6}$$

relative uncertainties

$$\frac{\delta N}{N} \approx 6 \cdot \frac{\delta E_T}{E_T}$$

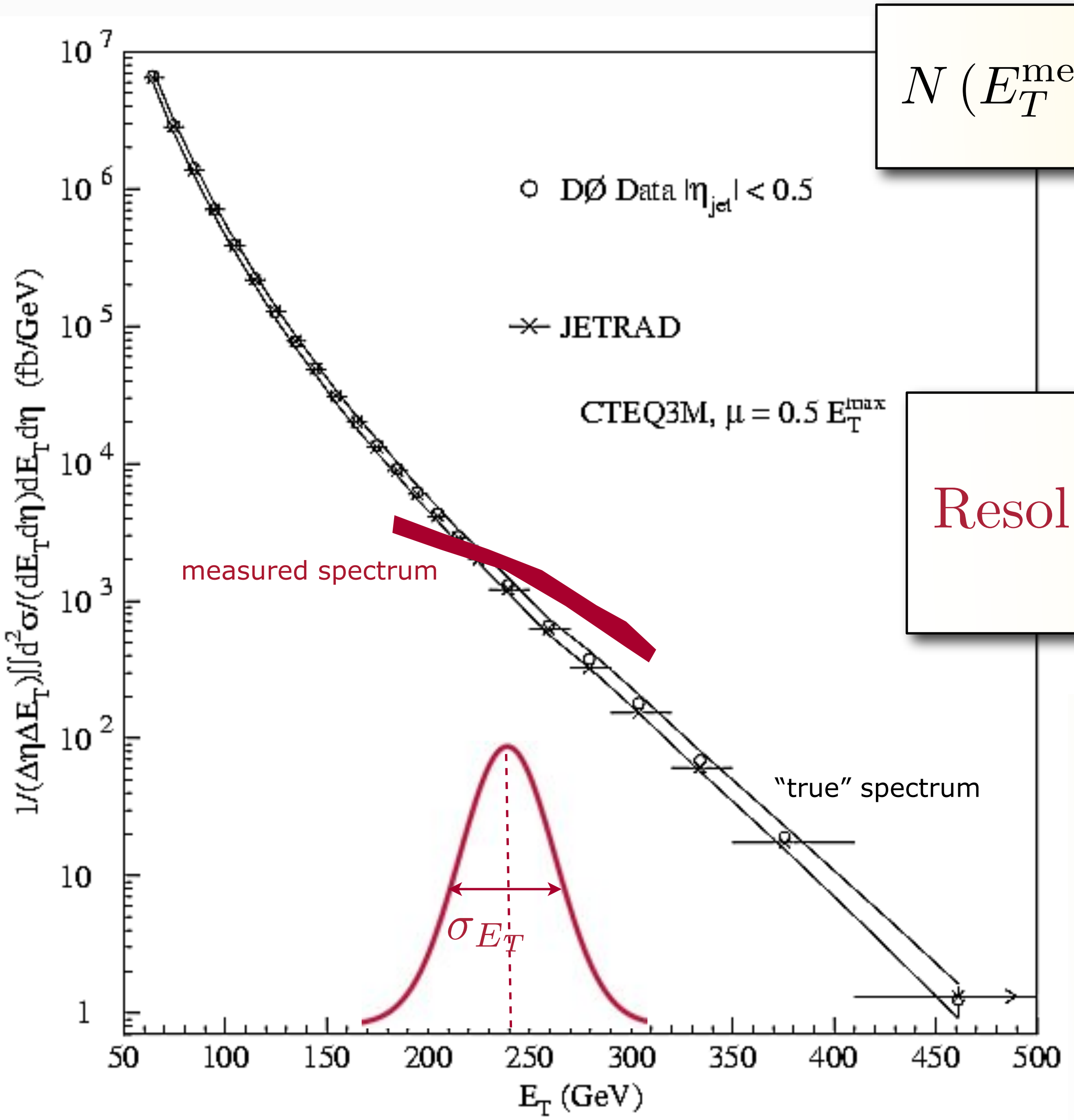
so beware:

eg. an uncertainty of **5%** on absolute energy scale (calibration)

➔ an uncertainty of **30%** (!) on the measured cross section

Problem 2 : Resolution

- The finite resolution can distort the spectrum
- Again : Critical because of very steeply falling spectrum!



$$N\left(E_T^{\text{meas}}\right) = \int_0^\infty N\left(E_T^{\text{true}}\right) \cdot \text{Resol}\left(E_T^{\text{meas}}, E_T^{\text{true}}\right) \mathrm{d}E_T^{\text{true}}$$

eg. Gaussian resolution function

$$\text{Resol}\left(E_T^{\text{meas}}, E_T^{\text{true}}\right) \propto \exp\left[-\frac{\left(E_T^{\text{meas}} - E_T^{\text{true}}\right)^2}{\sigma_{E_T}^2}\right]$$

so beware:

A bad energy resolution can distort the true spectrum

➔ have to determine the energy resolution

➔ have to "unfold" the measured spectrum

➔ problem is minimized if bin width ~ σ_{E_T}

The Luminosity

$$\sigma_{\text{meas}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\varepsilon \, L}$$

Two possible approaches

$$\sigma_{meas} = \frac{N_{obs} - N_{bkg}}{\varepsilon \ L}$$

invert the problem

measure the luminosity from first principles

$$L = \frac{N_{obs} - N_{bkg}}{\epsilon \ \sigma_{theo}}$$

$$L = \frac{N_1 N_2 \nu_{orb} N_b}{2\pi\sigma_{eff}(x)\sigma_{eff}(y)} \equiv \frac{\dot{N}}{\sigma}$$

Needs a very precisely calculable process, eg. W and Z production, as well as low exp. uncertainties

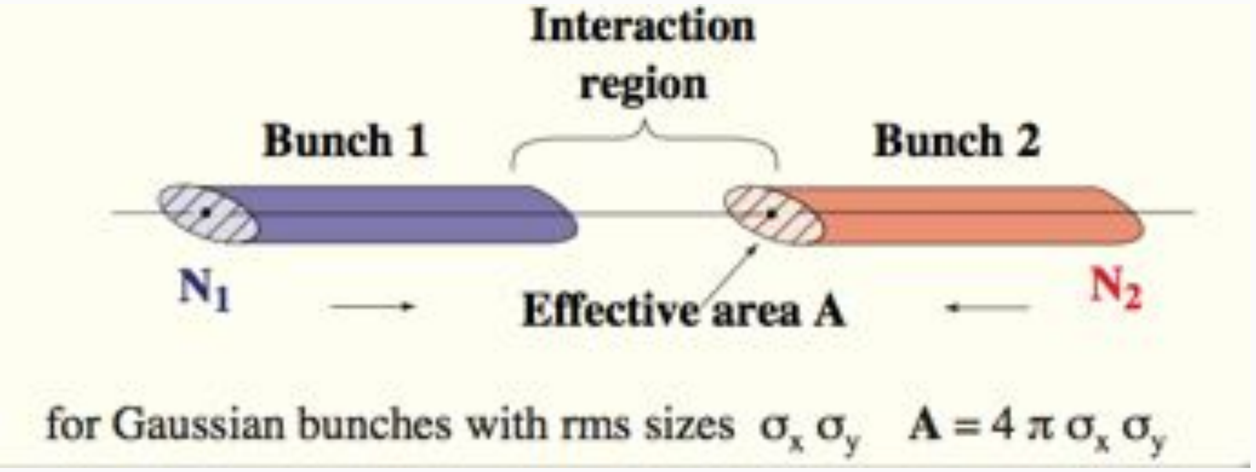
Have to measure:

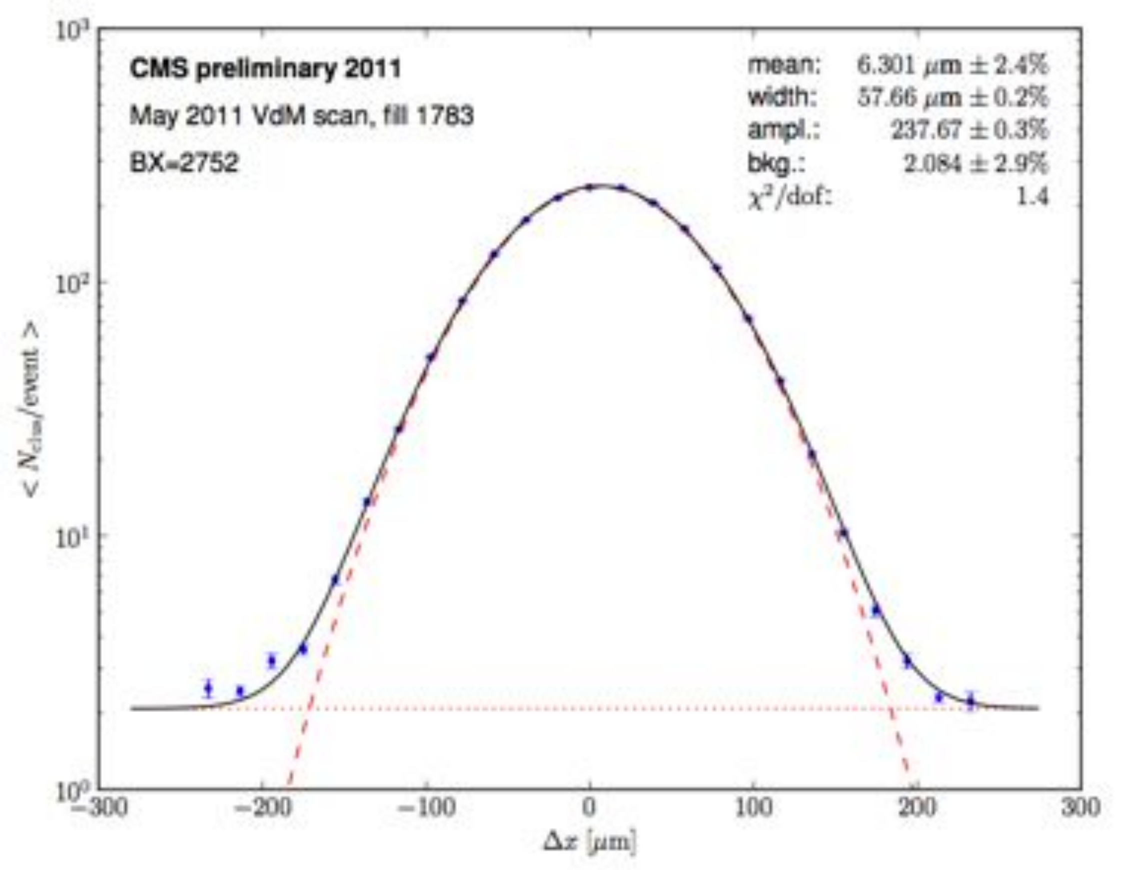
- beam currents
- effective beam size --> Van der Meer scan !
- then, after absolute calibration:

  take stable process to measure evolution in time, eg. number of counts in forward calorimeters

Van der Meer scans

- Move the beams relative to each other and monitor the rate of some basic process, eg. MinBias triggers





Source	Uncertainty (%)
Stability across pixel detector regions	0.3
Pixel gains and pedestals	0.5
Dynamic inefficiencies	0.4
Length-scale correction	0.5
Beam width evolution	0.6
Beam intensity - DCCT	0.3
Beam intensity - FBCT	0.5
Beam intensity - Ghosts	0.2
Scan-to-scan variations	1.5
Afterglow	1.0
Total	**2.2**