Vector bosons and direct photons

Lecture 1

John Campbell, Fermilab

Introduction

- I am a theorist interested in hadron-collider phenomenology.
- Main interest: higher order corrections in QCD.
- Author of next-to-leading order Monte Carlo code MCFM.

- Two lectures, today and tomorrow.
- For questions or comments:
  - discussion sessions tonight and tomorrow night;
  - or, email: johnmc@fnal.gov

- Some material taken from "QCD for Collider Physics" by Ellis, Stirling, Webber - excellent resource for further details on many subjects covered here.

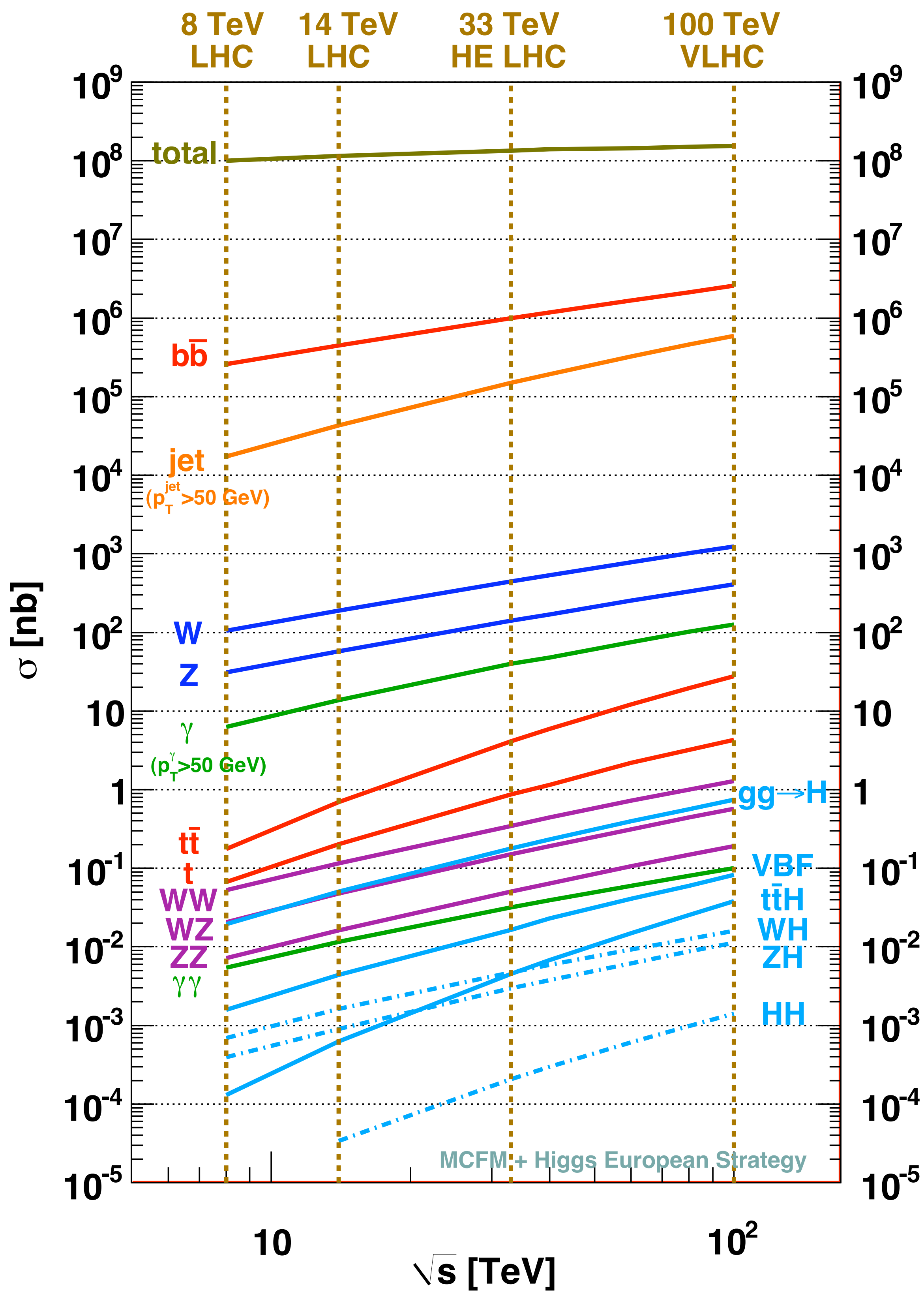
Outline of lectures

- Overview of vector boson basics.
- Underlying theory of W,Z production.
- Discussion of the direct photon process.
- Di-photon production.

- The importance of multi-boson production.
- Review of selected di-boson phenomenology.
- Beyond inclusive di-boson measurements.

Setting the scene

- Cross sections for producing W, Z bosons and photons are huge.
    - radiating additional jets (approx. factor of α_s) still leaves large cross sections.
    - multiple boson production still significant versus BSM rates.
- Experimentally important:
    - clean final states good for calibration (leptons, photons).
    - leptons, missing energy (+jets) crucial backgrounds.
- Theoretically important:
    - expect well-understood cross sections, test of new calculations.



Electroweak Feynman rules

- Electroweak interaction Lagrangian:

$$\begin{aligned}
\mathcal{L} &= \sum_f \bar\psi_f \left(i\partial\!\!\!/ - m_f - g_W \frac{m_f H}{2M_W} \right) \psi_f \\
&- \frac{g_W}{2\sqrt{2}} \sum_f \bar\psi_f (\gamma^\mu (1-\gamma_5) T^+ W_\mu^+ + \gamma^\mu (1-\gamma_5) T^- W_\mu^-) \psi_f \\
&- e \sum_f Q_f \bar\psi_f A\!\!\!/ \psi_f - \frac{g_W}{2\cos\theta_W} \sum_f \bar\psi_f \gamma^\mu (V_f - A_f \gamma_5) \psi_f Z_\mu
\end{aligned}$$

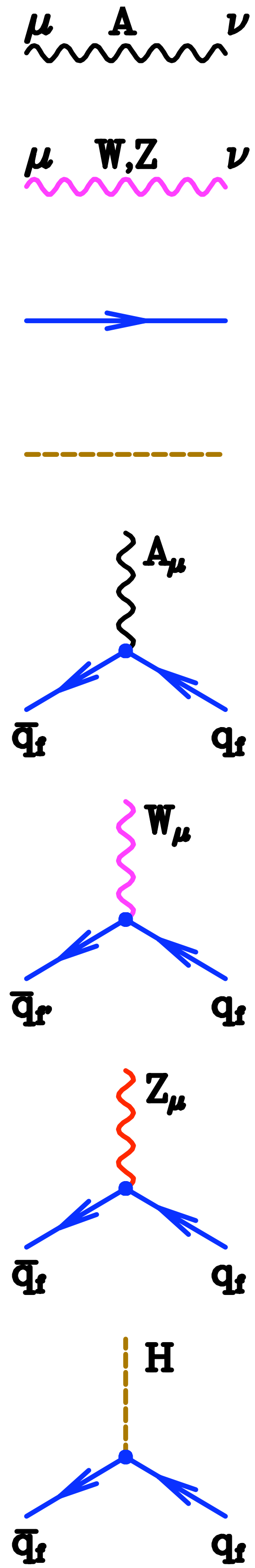
- W boson couples to left-handed fermions
- Z boson couples to both, different strengths:

$$(V_f - A_f\gamma_5) = \frac{V_f + A_f}{2}(1-\gamma_5) + \frac{V_f - A_f}{2}(1+\gamma_5)$$

  - vector and axial couplings in terms of weak isospin $T^3_f = \pm\frac{1}{2}$

$$\begin{aligned}
V_f &= T_f^3 - 2Q_f \sin^2\theta_W \\
A_f &= T_f^3
\end{aligned}$$

$$V_u \approx 0.2,\ V_d \approx -0.35,\ V_\nu = \tfrac{1}{2},\ V_e \approx -0.04$$
$$A_u = \tfrac{1}{2},\ \ A_d = -\tfrac{1}{2},\ \ A_\nu = \tfrac{1}{2},\ \ A_e = -\tfrac{1}{2}$$



$$[-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}] \frac{i}{q^2}$$

$$[-g^{\mu\nu} + \frac{q^\mu q^\nu}{M^2}] \frac{i}{(q^2 - M^2)}$$

$$\frac{i}{q\!\!\!/ - m}$$

$$\frac{i}{(q^2 - M_H^2)}$$

$$-ieQ_f\gamma_\mu$$

$$\frac{-ig_W}{2\sqrt{2}} \gamma^\mu (1-\gamma_5)(T^+)_{f'f} \qquad g_W = \frac{e}{\sin\theta_W}$$

$$\frac{-ig_W}{2\cos\theta_W} \gamma^\mu (V_f - A_f\gamma_5)$$

$$(V_f = T_f^3 - 2Q_f \sin^2\theta_W,\quad A_f = T_f^3)$$

$$\frac{-ig_W m_f}{2M_W}$$

W and Z decays

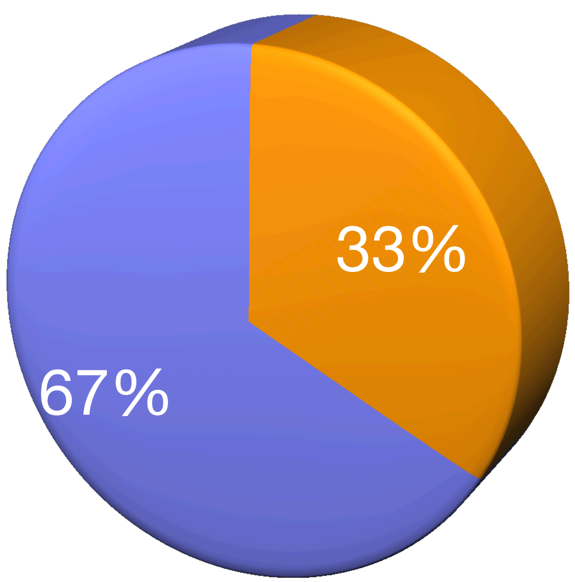
- Partial decay widths at leading order:

$$\Gamma(W^+ \to f\bar{f}') = C\,\frac{G_F M_W^3}{6\sqrt{2}\pi} \qquad \Gamma(Z \to f\bar{f}) = C\,\frac{G_F M_Z^3}{6\sqrt{2}\pi}\left(V_f^2 + A_f^2\right)$$

C=1 leptons / C=3 quarks

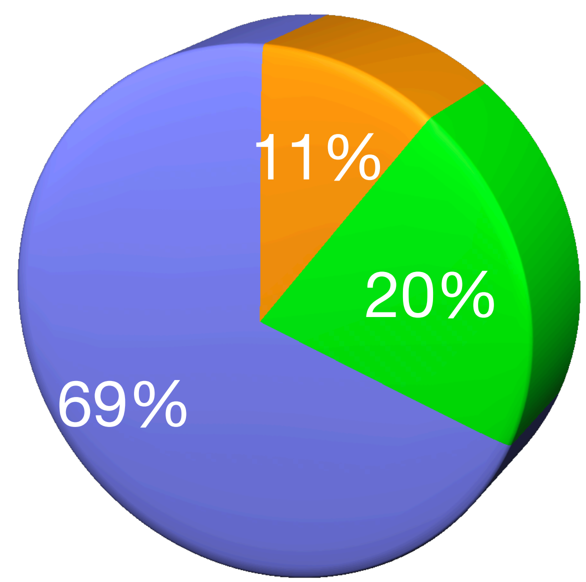
- W decays: 3 charged leptons (C=1), 2 open generations of quarks (C=3) $\Rightarrow$ $Br(W^+ \to e^+\nu) = 1/9$.

- Z decays: $V_e \approx 0$, $|A_e| = |A_\nu| = |V_\nu|$ $\Rightarrow$ $Br(Z \to \nu\nu) \approx 2 \times Br(Z \to e^+e^-)$



W

leptons
jets



Z

charged leptons
neutrinos
jets

- Large fraction of decays into difficult-to-measure modes.

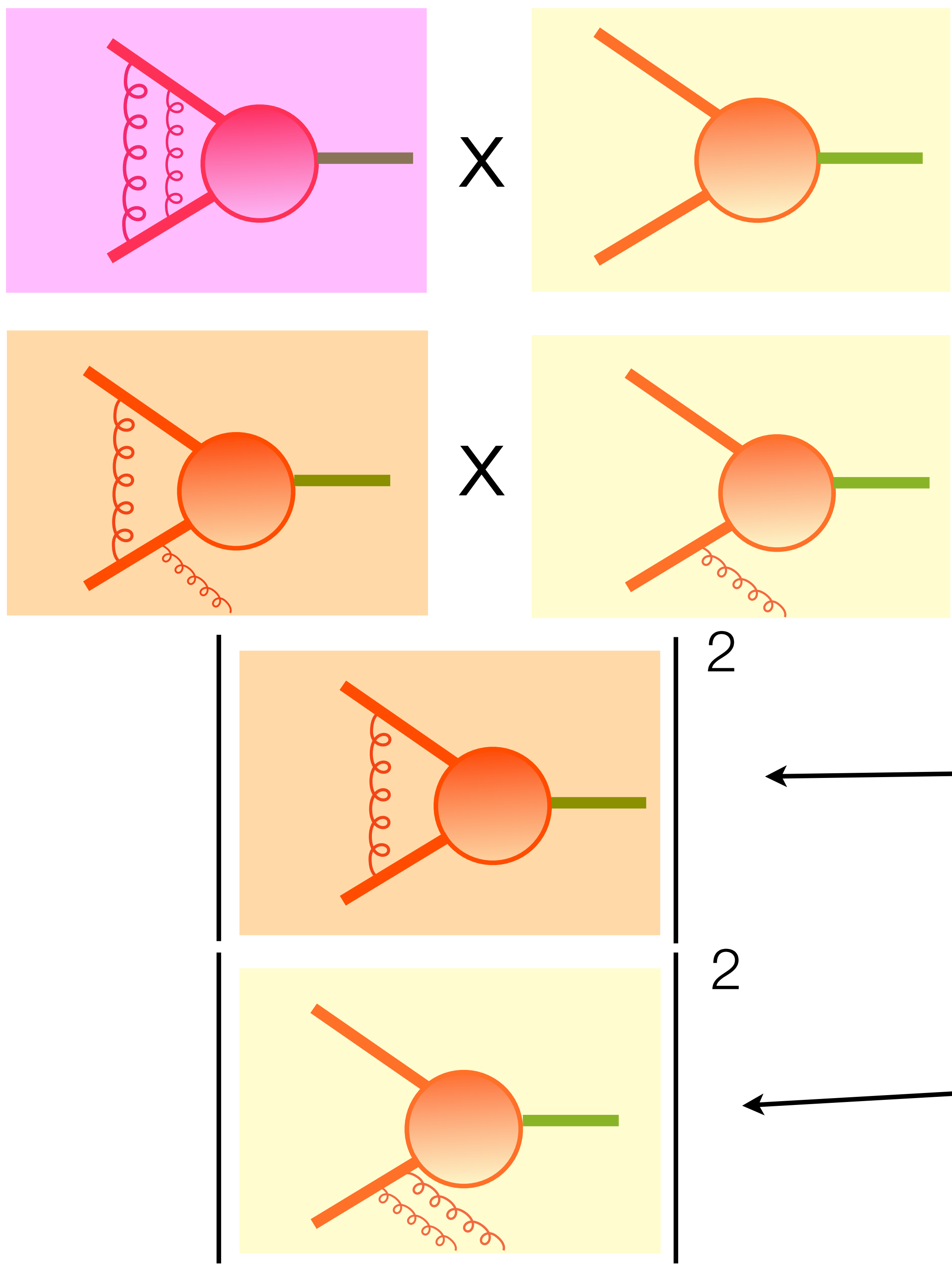
W and Z production

- You have already seen a sketch of the NLO corrections to these processes and discussed some of the simple phenomenology such as rapidity distns.
  - you will also get more later on (NLO and matching, pdf fits)
- Instead, I will focus on different aspects of W and Z production and the underlying theory.
- Historically, these processes have provided an essential role in extending the perturbative description to higher orders, beyond NLO QCD.
  - they are the simplest non-trivial calculations, containing only a single scale
  - an electroweak final state, so QCD corrections only occur in production
- Of course, improving the accuracy of the predictions important in its own right
  - very large cross sections for basic physics objects
  - improved extractions of fundamental quantities, e.g. M_W, pdfs
- First up: going from NLO to NNLO QCD.

2→1 processes at NNLO

(out of my purview, but same story for gg→H)

- Much more than just virtual/real combination at NLO - many ways of making g_s^4.

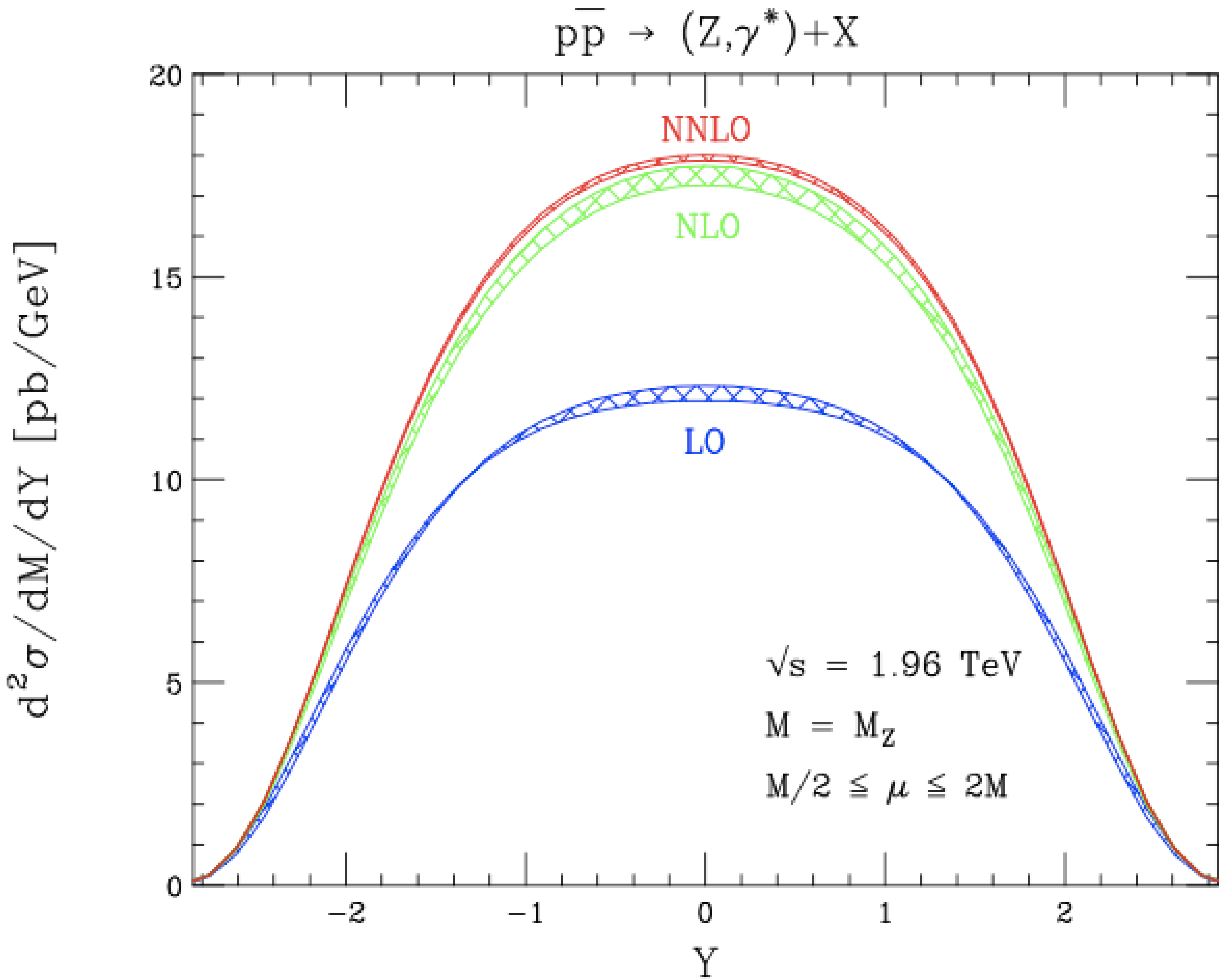


needs 2-loop amplitude, for many years the unknown ingredient

known one-loop corrections, but more soft and collinear divergences

on the surface looks the easiest; in fact, untangling structure of singularities the key to the calculation

NNLO result



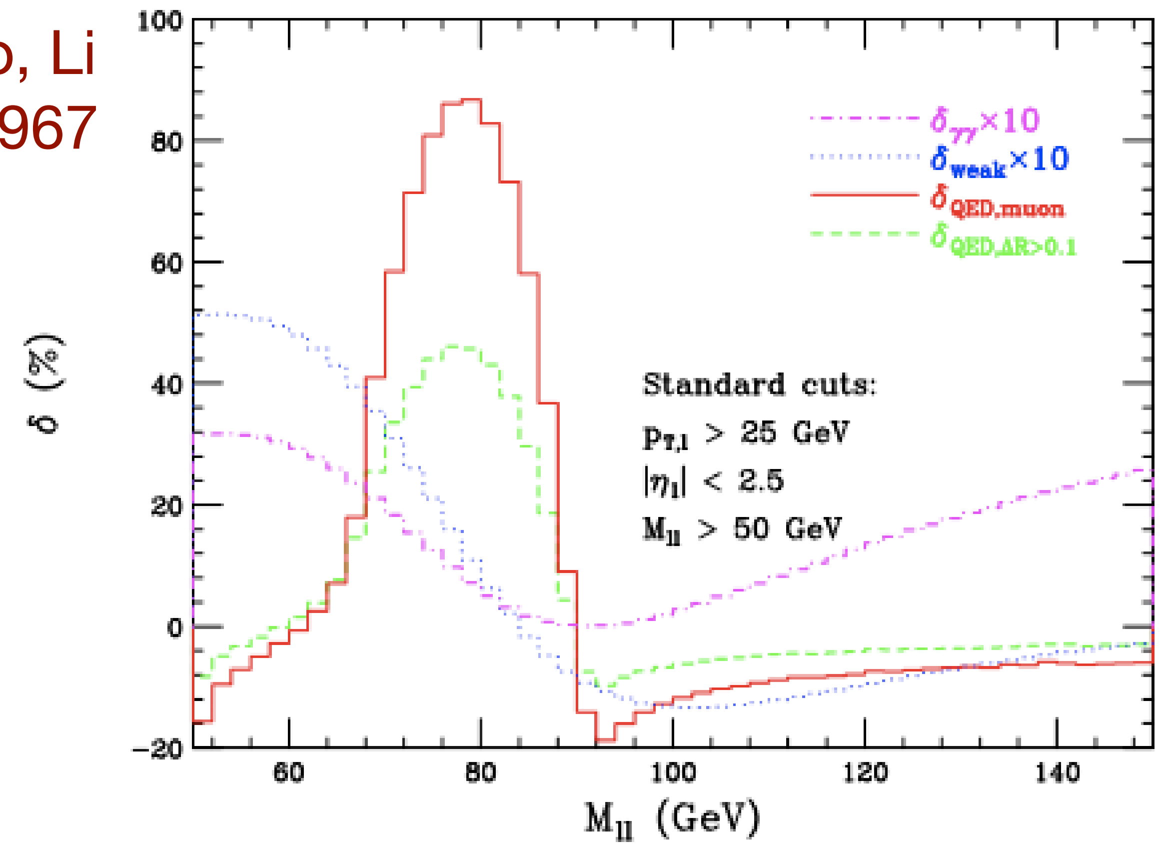
Anastasiou, Dixon, Melnikov, Petriello (2004)

- Very large correction from LO to NLO does not repeat from NLO to NNLO → stabilisation of the expansion.
- NNLO outside NLO error estimate, now has error of a few percent.

Beyond NNLO QCD

- Numerically, expect NNLO QCD (α_s^2) to be at the same order as NLO QED and electroweak effects (α).
  - virtual loops of photons, W, Z bosons;
  - real radiation of photons;
  - since W and Z bosons are massive and are explicitly reconstructed in the detector (and put in different event samples) no need to add their effects.
- EW effects especially important near the Z peak.
- Sensitivity to the definition of the lepton ("bare" or "dressed", recombined with photon).
- Should include photon-induced contributions $\gamma\gamma \to \ell^+\ell^-$.
- Open issue: how to combine QCD and QED contributions.

Petriello, Li
1208.5967

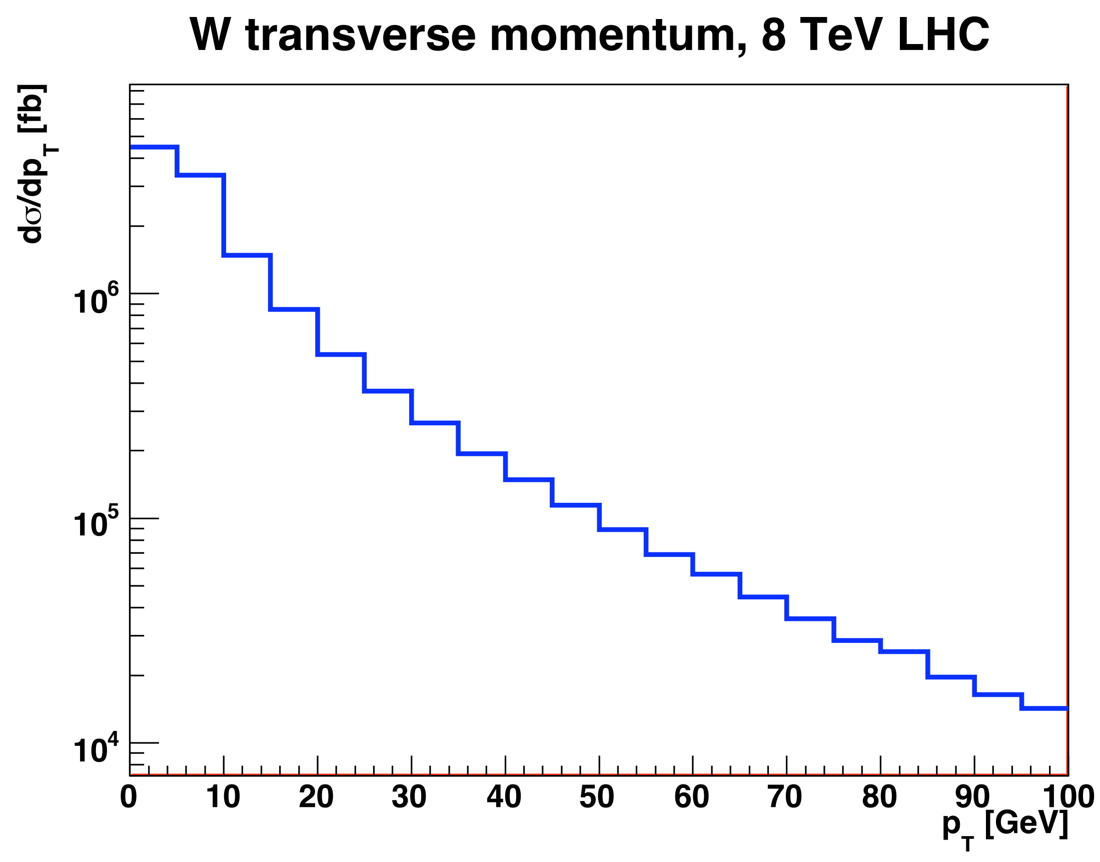


A different approach

- Extending the perturbative description order-by-order is one tactic.
- However there are limitations present at each order that can be better-handled with a different approach.
    - usually associated with the extra radiation present at higher orders.
- Start by looking at the transverse momentum distribution of the W as given by a NLO calculation of the total rate.

1) All of the genuine NLO corrections, from the 1-loop virtual diagrams, enter at p_T=0. In fact they are large and negative → get any answer you want in the first bin, depending on the bin width.

2) prediction for any p_T>0 is really just a leading-order one, from real radiation diagrams.

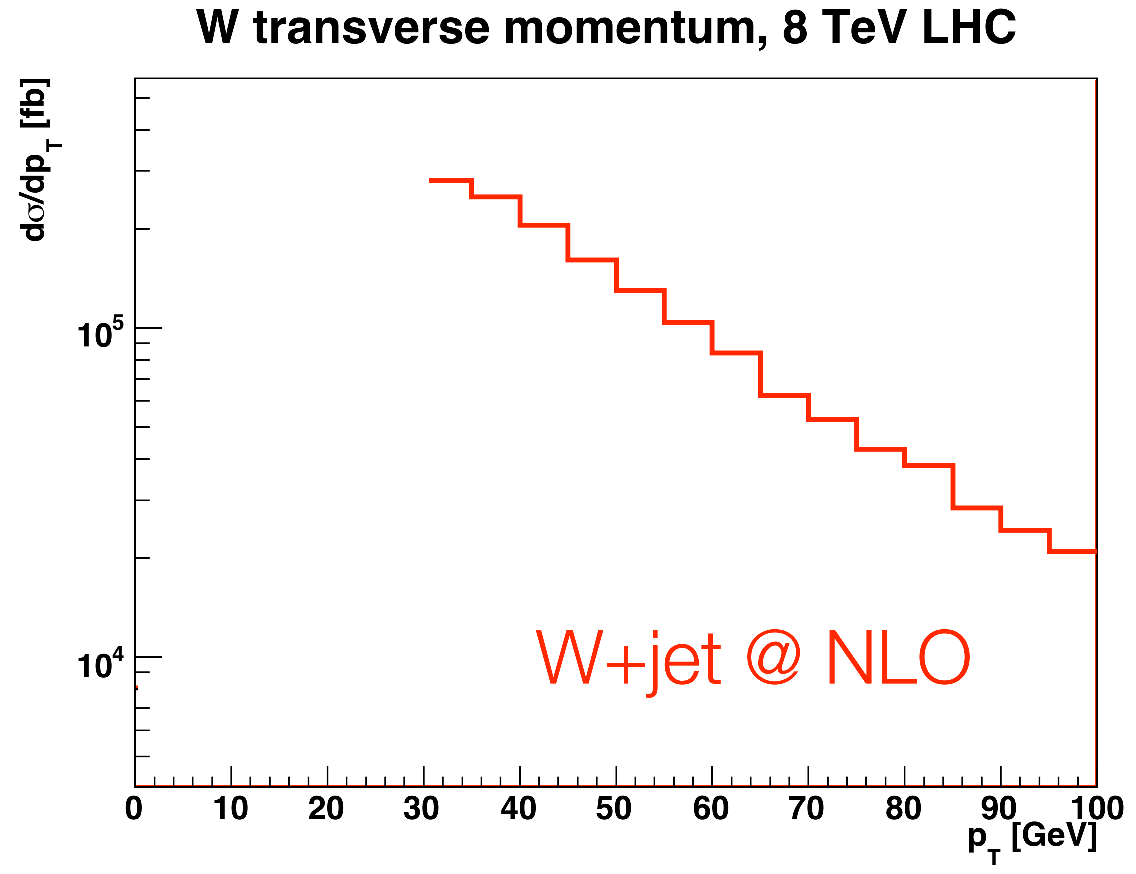


One approach

- Easiest to tackle the second problem first: improving prediction at high p_T.
- Recognize that at large p_T we can just compute the corrections to the process,

$$pp \to W + \text{jet}$$

  with the jet providing a non-zero recoil even at LO.
- The calculation requires the definition of a jet, specifying a minimum transverse momentum; W p_T with NLO accuracy above this cut (25 GeV here).



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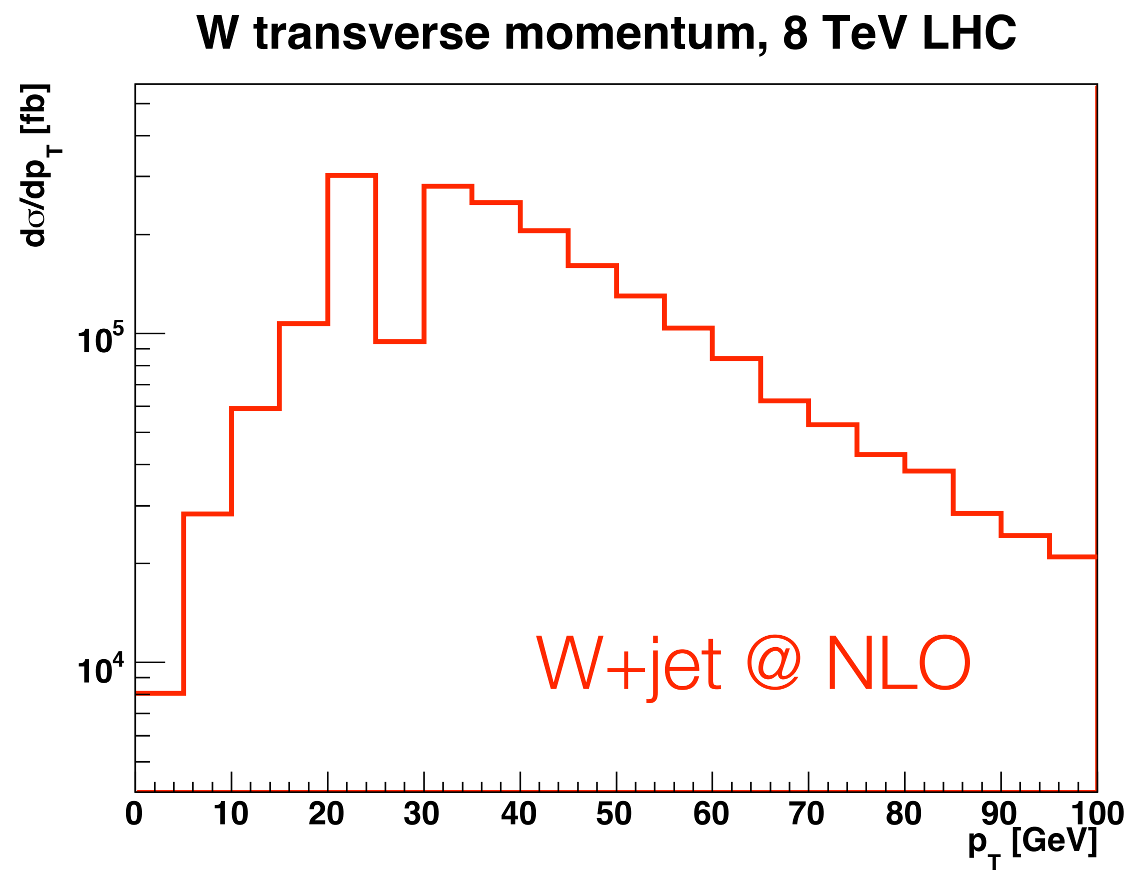
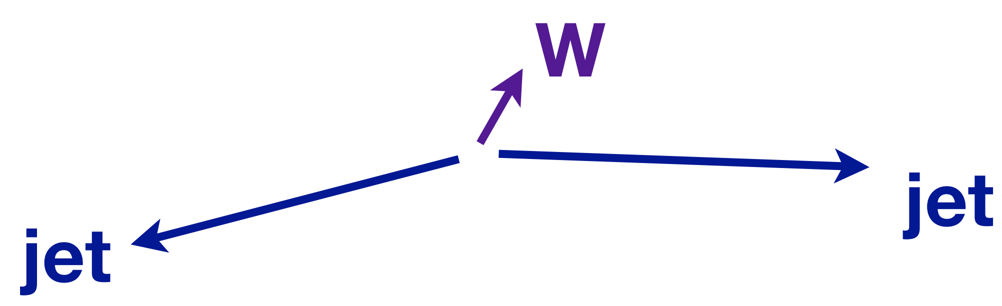


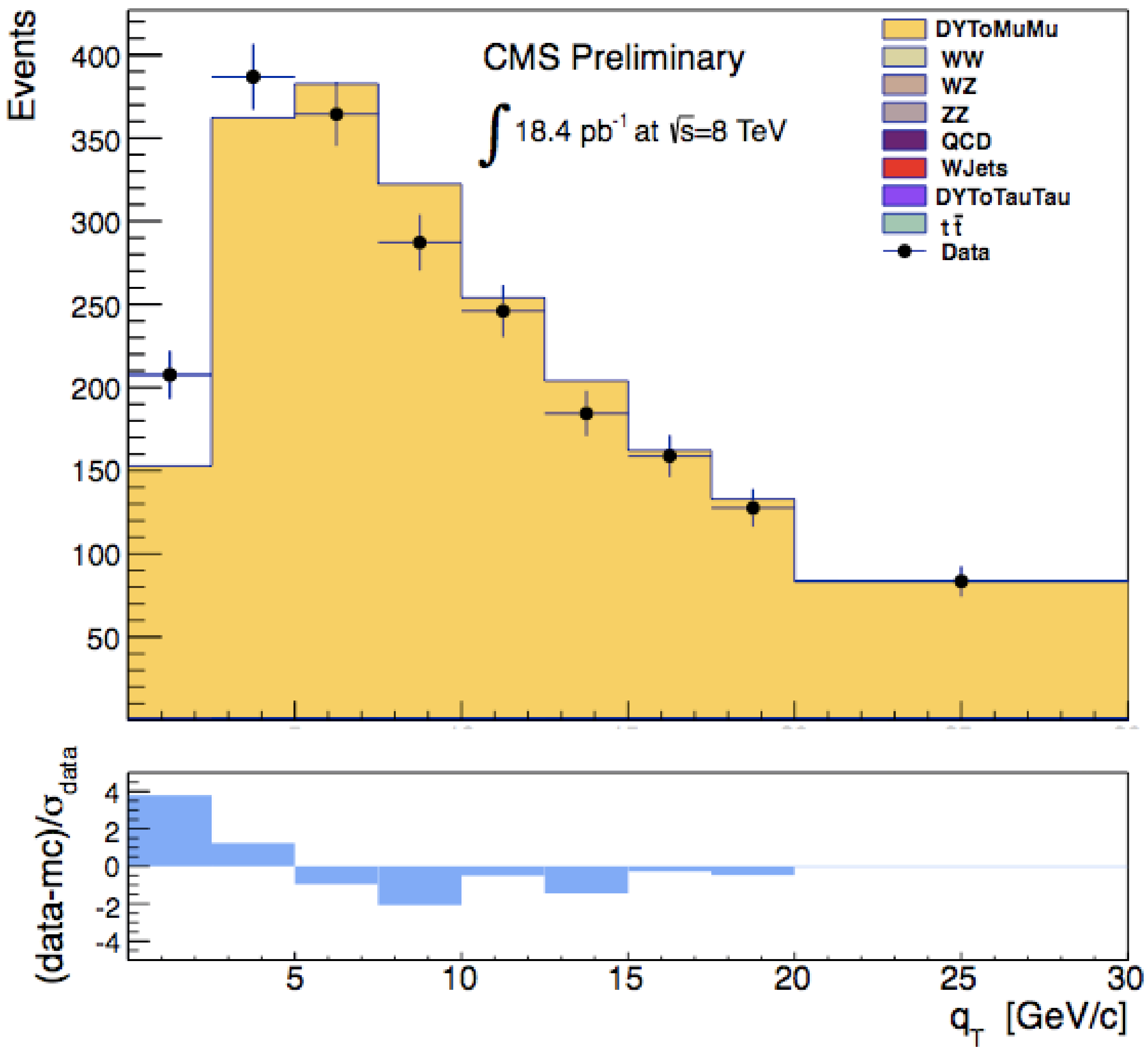
- Below the jet cut, W p_T is populated by configurations with two almost-balancing jets → LO only.



- Prediction unreliable adjacent to jet cut.

What now?

- At high p_T the prediction does not depend on the cut
  - how small can we take it?
  - how can the behaviour at small p_T be fixed?
- In particular, how can a perturbative description produce turn-over like the one seen in data?
- Solution: need to account for all possible recoils against multiple partons in a systematic fashion.
  - identify relevant terms in the cross section and include effects to all orders → resummation.

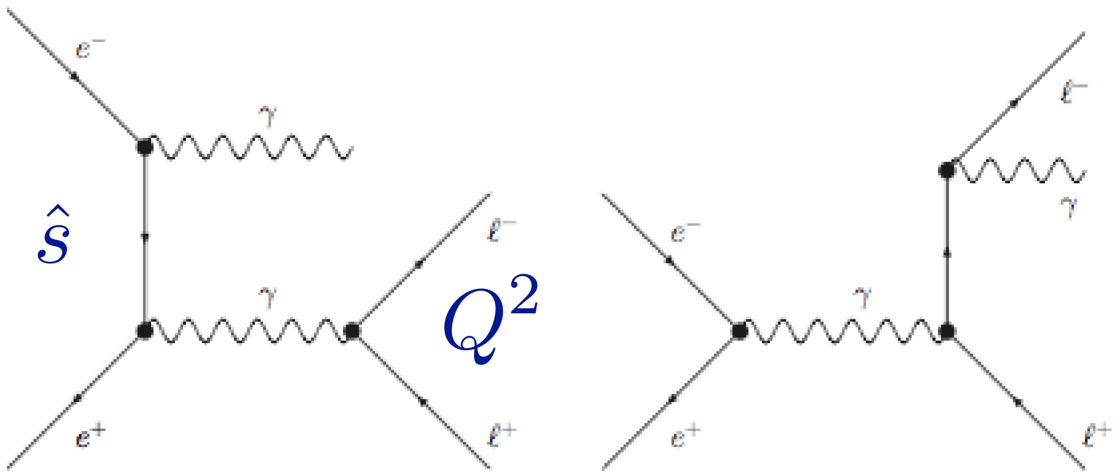


Introduction to resummation

- To have a feeling for how resummation works, simplest to back off to a lepton collider: trade quarks for electrons and gluons for photons.

Parisi and Petronzio (1979)

- Look at the form of the cross section at small transverse momenta; consider virtual photon only (no Z).



Definition of kinematics:

$$Q = m_{\ell^+\ell^-}\,, \quad \hat{s} = m_{e^+e^-}$$

- Close to partonic threshold differential cross section has the form:

$$\frac{\mathrm{d}\hat{\sigma}_R}{\mathrm{d}Q_\perp^2} = \hat{\sigma}_0 \frac{\alpha}{\pi} \frac{1}{Q_\perp^2} \left[\log \frac{\hat{s}}{Q_\perp^2} + \mathcal{O}(1)\right] \longrightarrow \mathrm{d}\hat{\sigma}_R \approx \hat{\sigma}_0 \frac{\alpha}{\pi} \frac{\mathrm{d}Q_\perp^2}{Q_\perp^2} \log \frac{\hat{s}}{Q_\perp^2}$$

- Can integrate out Q_T up to given p_T: $\displaystyle\int \mathrm{d}\hat{\sigma}_R = \hat{\sigma}_0 \frac{\alpha}{\pi} \int_0^{p_\perp^2} \frac{\mathrm{d}Q_\perp^2}{Q_\perp^2} \log \frac{\hat{s}}{Q_\perp^2}$

Sketch of DLLA

- As it stands we cannot analyse the behaviour as $Q_T \to 0$: problem caused by the usual collinear divergence.
- But we know that in a NLO calculation this divergence is cancelled by the virtual loop contribution at exactly $Q_T=0$
  - result is then finite, giving an (α/π) correction to σ_0
- Dropping this term since it is not logarithm-enhanced, we thus have:

$$\hat{\sigma}_0 = \int (\mathrm{d}\hat{\sigma}_R + \mathrm{d}\hat{\sigma}_V) = \int_0^{p_\perp^2} (\mathrm{d}\hat{\sigma}_R + \mathrm{d}\hat{\sigma}_V) + \hat{\sigma}_0 \, \frac{\alpha}{\pi} \int_{p_\perp^2}^{\hat{s}} \frac{\mathrm{d}Q_\perp^2}{Q_\perp^2} \log \frac{\hat{s}}{Q_\perp^2}$$

full result with correction dropped

what we wanted on previous slide (+σ_V)

an integral we can do!

- Rearrange and do the integral:

$$\int_0^{p_\perp^2} (\mathrm{d}\hat{\sigma}_R + \mathrm{d}\hat{\sigma}_V) = \hat{\sigma}_0 \left(1 - \frac{\alpha}{\pi} \int_{p_\perp^2}^{\hat{s}} \frac{\mathrm{d}Q_\perp^2}{Q_\perp^2} \log \frac{\hat{s}}{Q_\perp^2}\right)$$

$$= \hat{\sigma}_0 \left(1 - \frac{\alpha}{2\pi} \log^2 \frac{\hat{s}}{p_\perp^2}\right)$$

This is the double leading-log approximation (DLLA) - all single log and constant terms have been dropped.

Multiple emission

- Single photon contribution to cross section: $\hat{\sigma}_0 \left(1 + \epsilon^{(1)}\right) \equiv \hat{\sigma}_0 \left(1 - \frac{\alpha}{2\pi} \log^2 \frac{\hat{s}}{p_\perp^2}\right)$
- Factorization in the soft limit leads to an (approximate) simple form for *n*-photon contribution:

$$\epsilon^{(n)} = \frac{1}{n!} \left(-\frac{\alpha}{2\pi} \log^2 \frac{\hat{s}}{p_\perp^2}\right)^n$$

- At this point straightforward to account for multiple photon emissions:

$$\Sigma(p_\perp^2) \equiv \hat{\sigma}_0 \sum_{n=0}^{\infty} \epsilon^{(n)} = \hat{\sigma}_0 \sum_{n=0}^{\infty} \frac{1}{n!} \left(-\frac{\alpha}{2\pi} \log^2 \frac{\hat{s}}{p_\perp^2}\right)^n = \hat{\sigma}_0 \exp\left(-\frac{\alpha}{2\pi} \log^2 \frac{\hat{s}}{p_\perp^2}\right)$$

Sudakov form factor: no emissions harder than p_T

- Recover differential distribution by taking derivative:

$$\frac{d\Sigma(p_\perp^2)}{dp_\perp^2} = \hat{\sigma}_0 \frac{\alpha}{\pi} \left(\frac{1}{p_\perp^2} \log \frac{\hat{s}}{p_\perp^2}\right) \exp\left(-\frac{\alpha}{2\pi} \log^2 \frac{\hat{s}}{p_\perp^2}\right)$$

finite as $p_T \to 0$
(tends to zero)

Comments

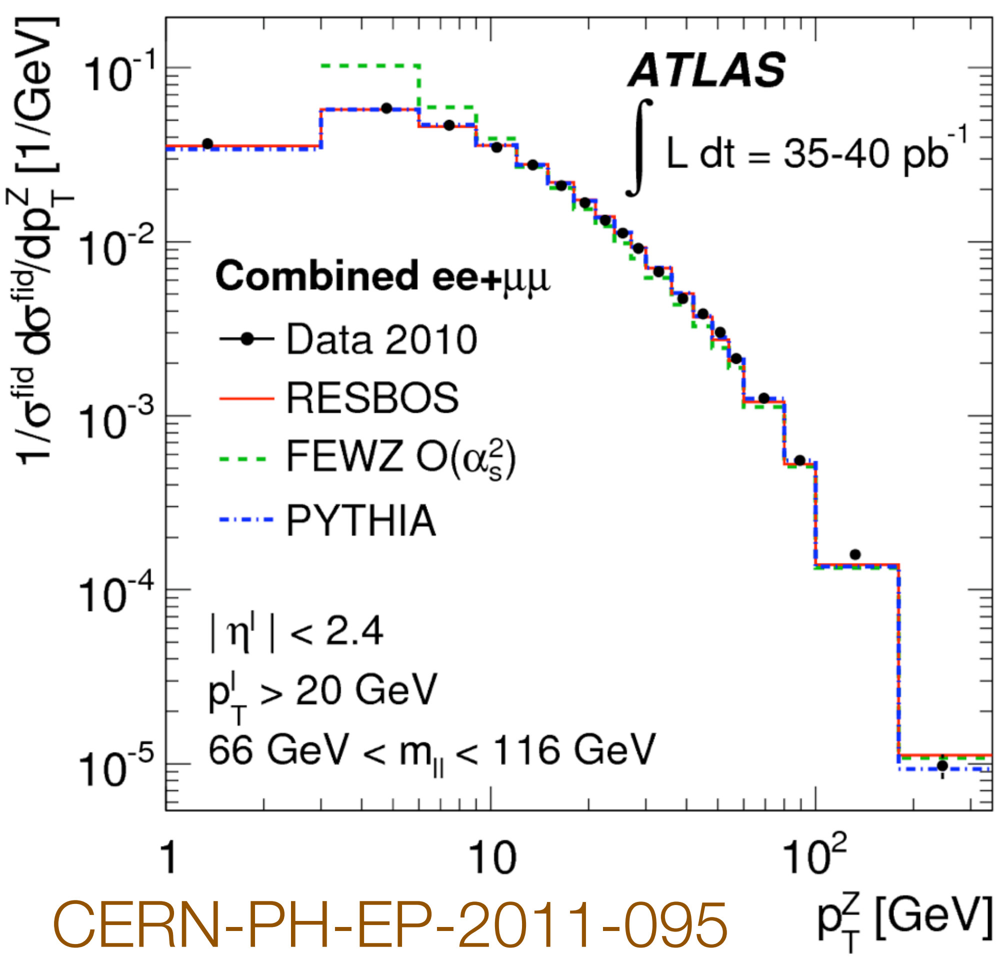
- This is far from the end of the story:
    - although there is no divergence, the cross section is now too suppressed.
    - the behaviour is modified by sub-leading logarithms.
    - the treatment of multiple emission is also over-simplified, since emissions are all considered independent with no accounting for mom. conservation.
    - a proper treatment of this is beyond the scope of these lectures, but involves Fourier-transforming from momentum to impact parameter space.
- Recipe to get back to QCD:
    - remember effect of colour, so additional factor of C_F
    - go from e.m. to strong coupling, remembering dependence on scale

$$\longrightarrow \exp\left(-\frac{\alpha_s(p_\perp^2) C_F}{2\pi} \log^2 \frac{\hat{s}}{p_\perp^2}\right)$$

(additional complications for very small p_T due to Landau pole)

Resummation in action

- More complicated than presented here:
  - accounts for momentum conservation
  - matching onto fixed order form at high p_T



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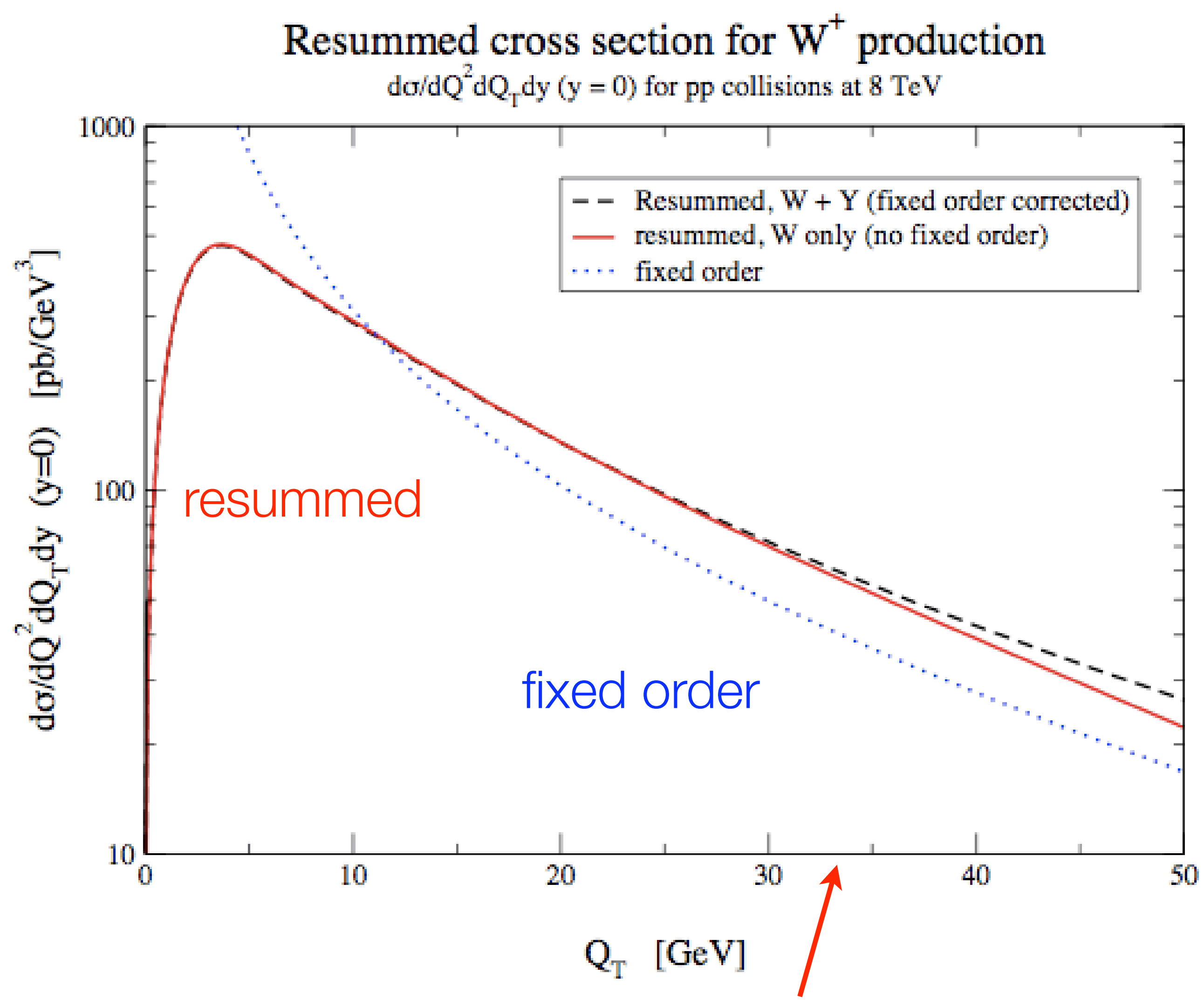


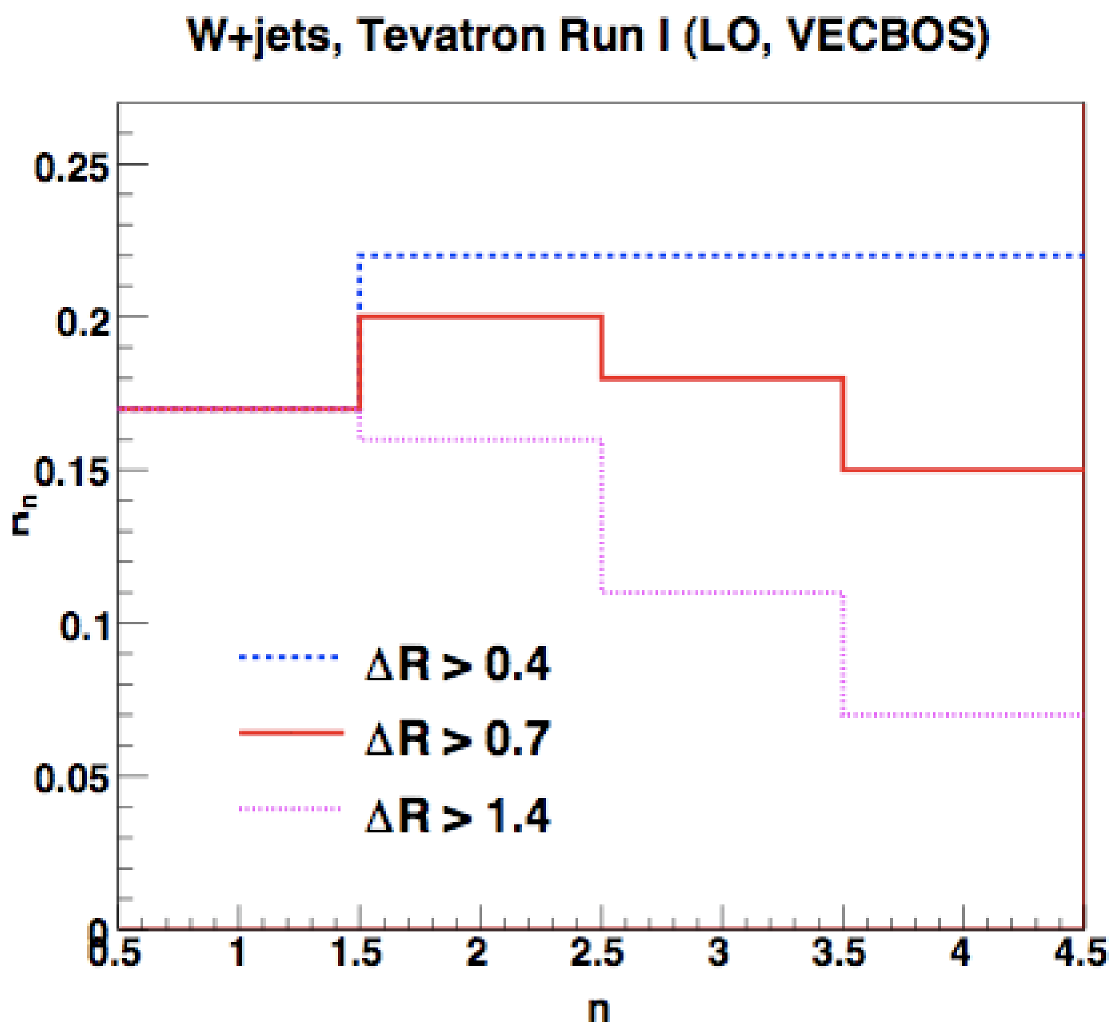
- Collins-Soper-Sterman ("CSS") resummation formalism, as implemented in RESBOS code.
- effect of leading logs also accounted for in standard MC procedure, e.g. Pythia.

W,Z + jets

- Go back to the higher order corrections we were considering before and now categorise by the number of jets in the final state, i.e. consider W+n jet, Z+n jet production.
- Motivation from both sides again:
  - final states with leptons, missing transverse momentum, jets
    - basic experimental signatures of New Physics, e.g. “MET+jets” SUSY
    - backgrounds to top production (W+jets) and Higgs studies
  - need to be understood to good precision
- At the forefront of developing theoretical tools on the “multiplicity frontier”
  - computation of amplitudes involving many jets, NLO corrections
  - systematic improvement of parton shower predictions - matching, merging and the inclusion of higher-order corrections

LO predictions

- Instrumental in developing (very efficient) recursion relations for computing helicity amplitudes.
- Berends-Giele recursion implemented in VECBOS (1990).
  - first calculation of W+4 jets, leading background to top production.

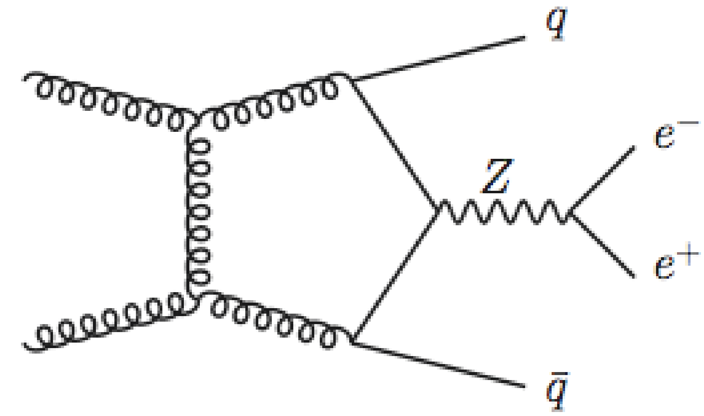


Similar recursive techniques now used in ALPGEN, SHERPA, Madgraph

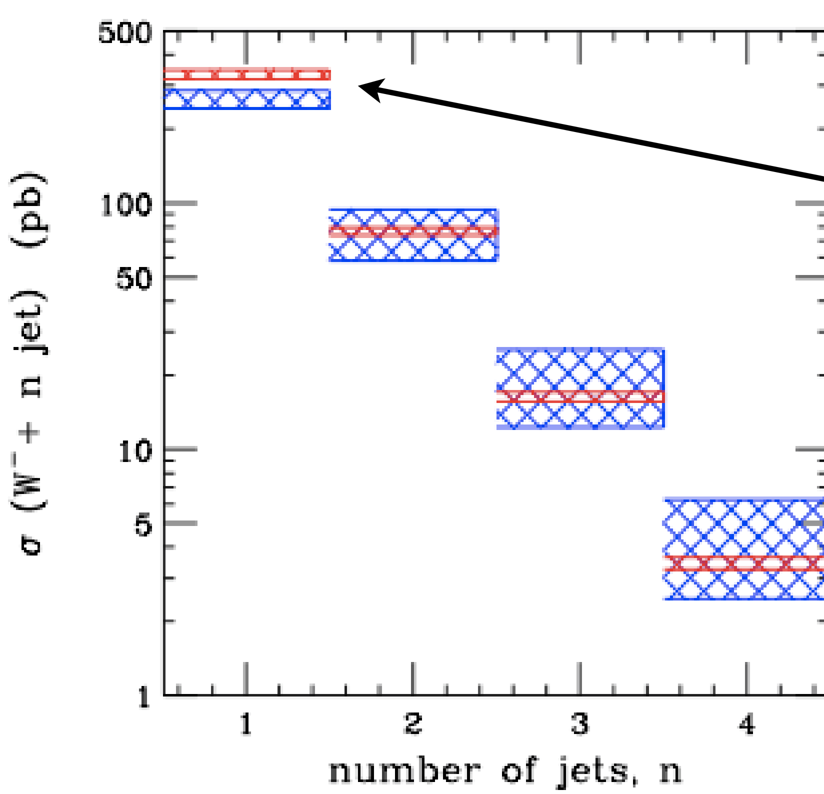
Useful observation about the scaling of the cross section with additional jets:

$$R_n = \frac{\sigma(W + n \text{ jets})}{\sigma(W + (n-1) \text{ jets})}$$

W/Z + jets at NLO



- Moving to jets (plural) requires evaluation of "pentagon" and higher-point loop integrals.
- V+2 jet case could be handled with usual technology but more than that required new methods.
- This inspired the rise of analytic and numerical on-shell unitarity techniques that form the basis of the loop calculations inside the latest theoretical tools
  - e.g. BlackHat, GoSam and aMC@NLO. (c.f. F. Krauss lectures)
- In the arena of V+jets, BlackHat+SHERPA provides predictions for for up to 5 additional jets.
- Scale-dependence of cross-sections reduced from LO to NLO.

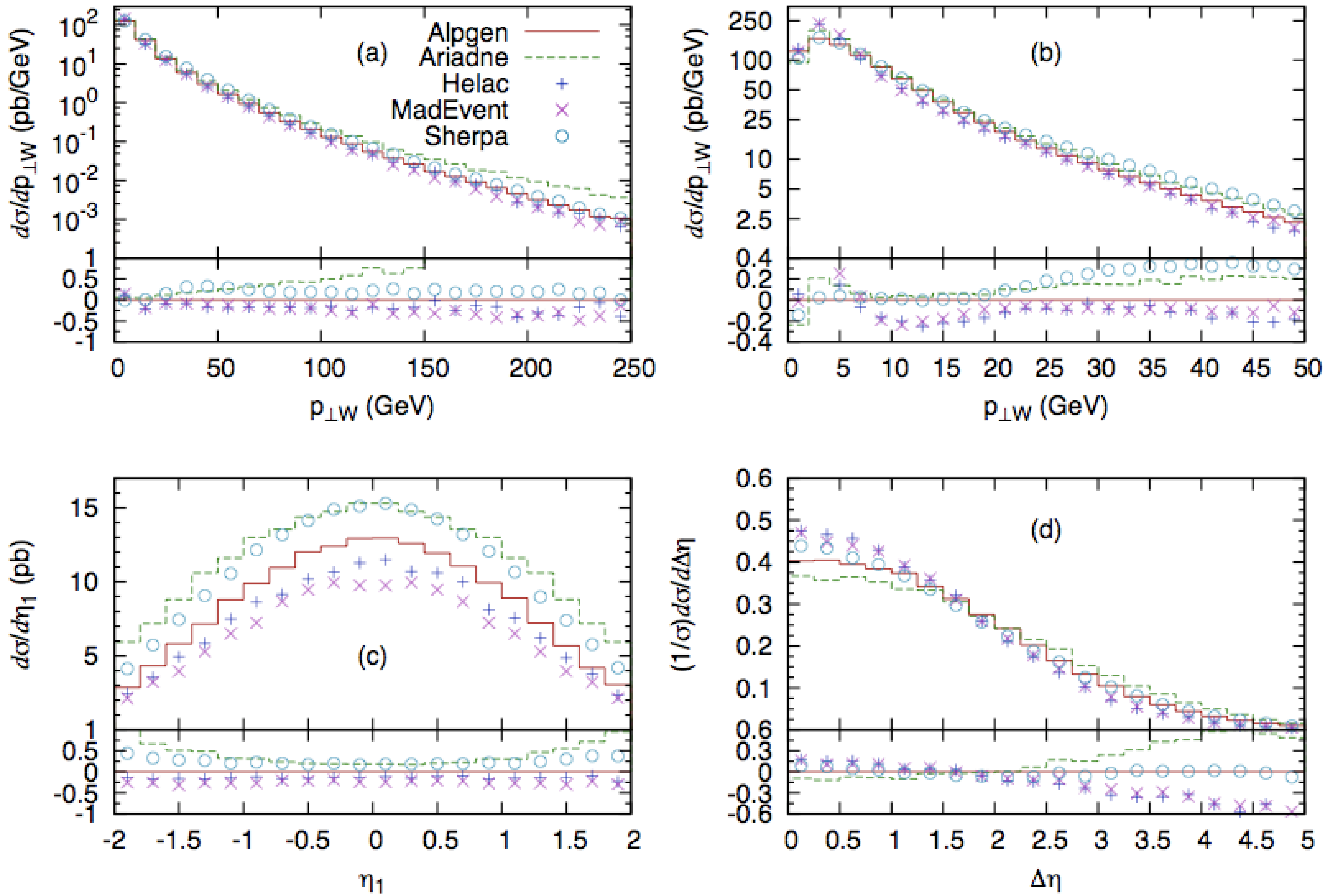


note unusual behaviour for V+1 jet; caused by inclusion of the effect of incident gluons for the first time at NLO

Improved parton showers

- Test bed for merging schemes at LO.

Alwall et al (2007)



Recent comparison with data

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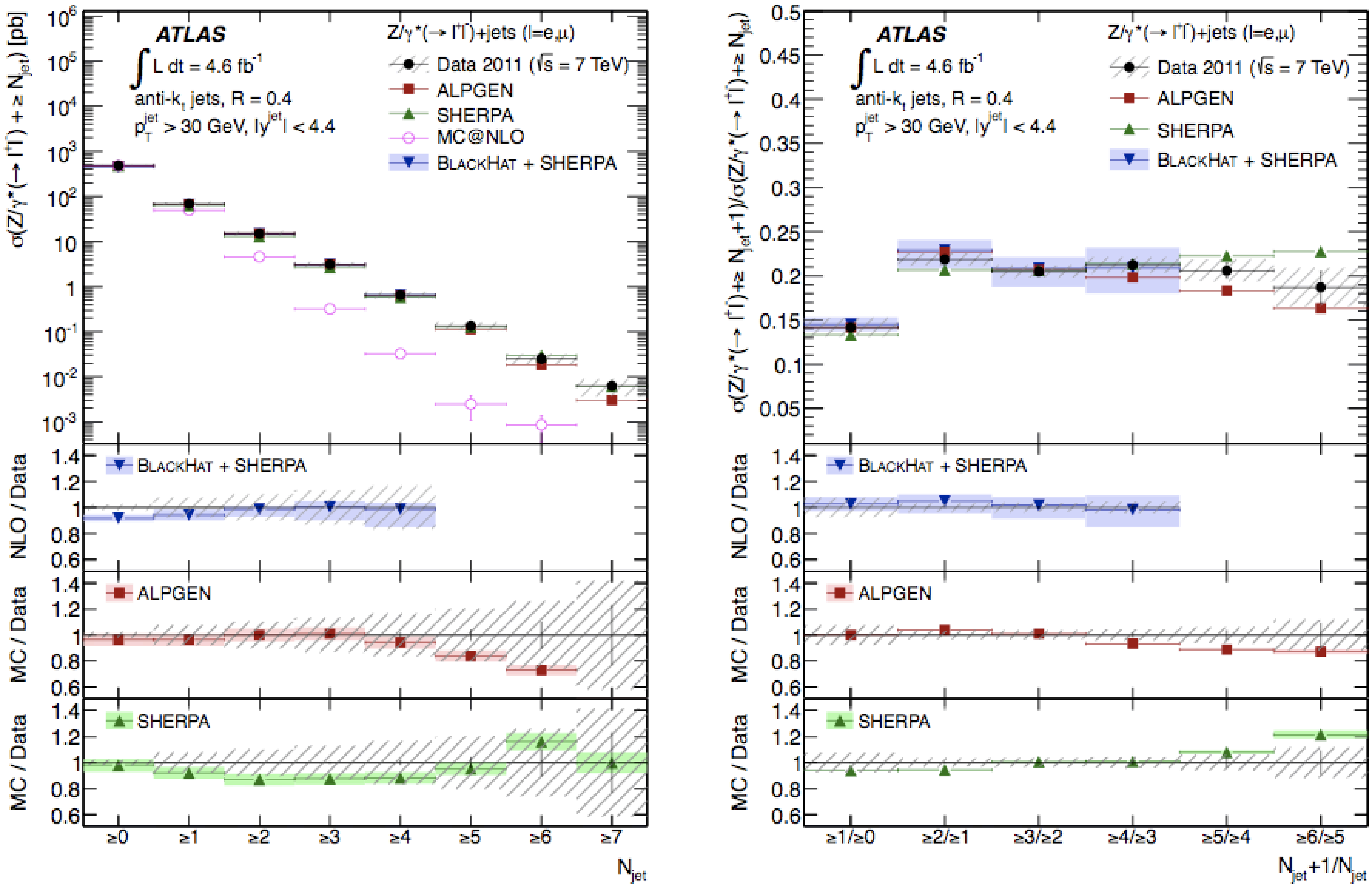
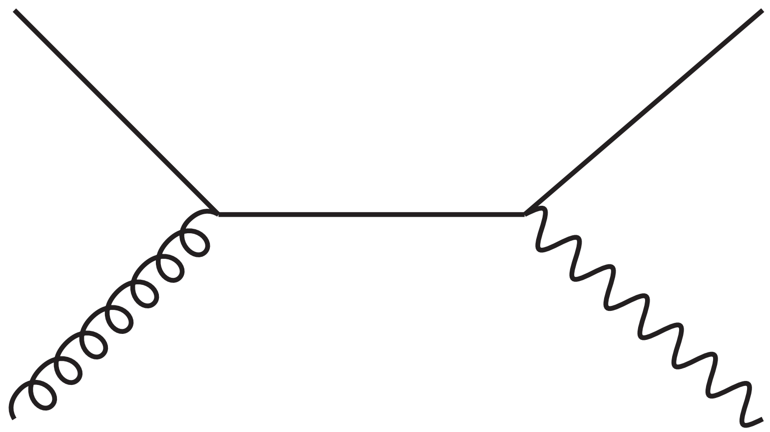
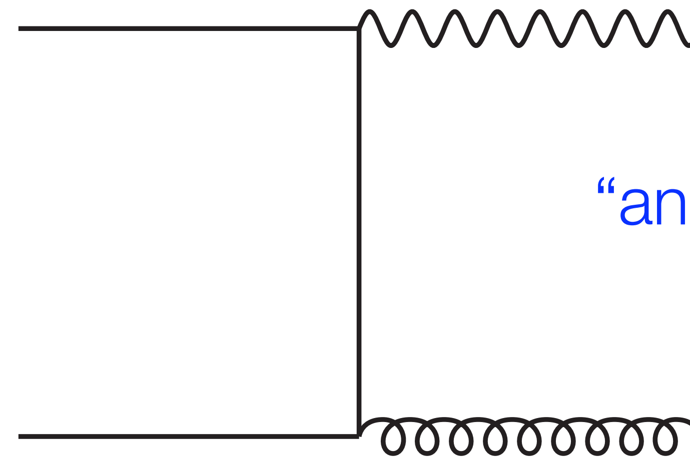


Direct photon production

- Unlike W and Z production, 2→2 process involving a jet, proceeding through quark- and gluon-initiated channels.

“Compton”



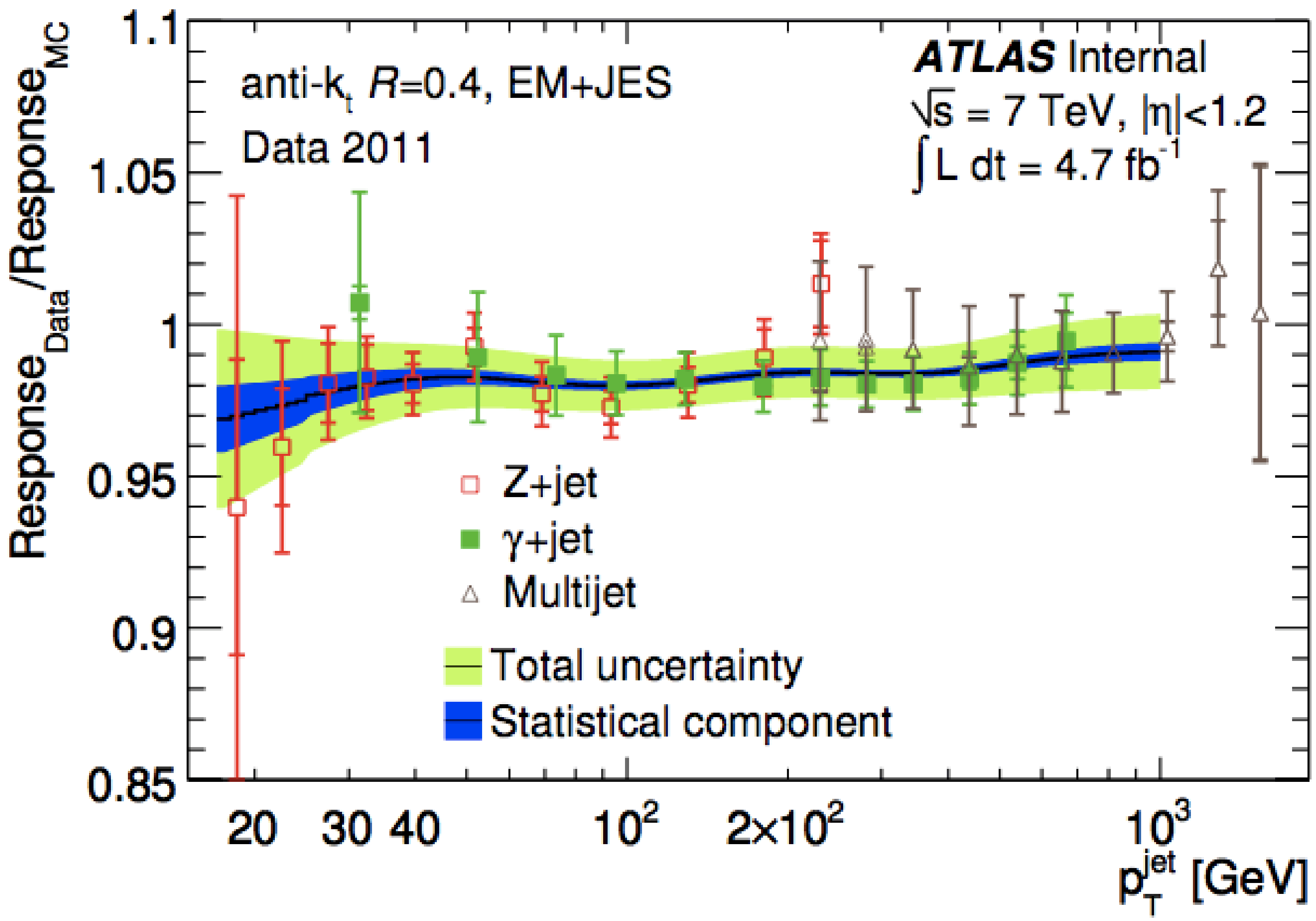


“annihilation”

- Leading order kinematics: p_T(photon) = p_T(jet)
  - significance for calibrating detector performance -- well-measured photon probes response of hadronic calorimeters;
  - used to measure jet energy scale (JES) and its uncertainty.

JES determination

- Recent ATLAS JES study: ATLAS-CONF-2013-004



- Photon+jet most important for $100 < p_T(\text{jet}) < 600$ GeV.

Amplitudes for photons and jets

- From theoretical point of view, much in common with jet production.
- For example, consider a helicity amplitude for the 2-jet (i.e. 4-parton) process:

$$0 \to \bar{q}^+(p_1) + q^-(p_2) + g^-(p_3) + g^+(p_4)$$

  (this is a MHV amplitude - two partons of one helicity, remainder opposite)

- At leading order, amplitude has two color-ordered contributions

$$\mathcal{M}(\bar{q}_1^+, q_2^-, g_3^-, g_4^+) = ig^2 \left[(T^{a_3}T^{a_4})_{i_2 i_1} M(\bar{q}_1^+, q_2^-, g_3^-, g_4^+) + (T^{a_4}T^{a_3})_{i_2 i_1} M(\bar{q}_1^+, q_2^-, g_4^+, g_3^-) \right]$$

  that can be written as simple expressions in terms of spinor products:

$$M(\bar{q}_1^+, q_2^-, g_3^-, g_4^+) = \frac{\langle 1\,3\rangle\langle 2\,3\rangle^3}{\langle 1\,2\rangle\langle 2\,3\rangle\langle 3\,4\rangle\langle 4\,1\rangle},$$

$$M(\bar{q}_1^+, q_2^-, g_4^+, g_3^-) = -\frac{\langle 1\,3\rangle\langle 2\,3\rangle^3}{\langle 1\,2\rangle\langle 2\,4\rangle\langle 3\,4\rangle\langle 3\,1\rangle}$$

$$\langle i\,j\rangle = \langle i-|j+\rangle = \bar{u}_-(p_i)u_+(p_j)$$

$$[i\,j] = \langle i+|j-\rangle = \bar{u}_+(p_i)u_-(p_j)$$

$\langle i\ j\rangle \sim \sqrt{s_{ij}}$ (up to a phase)

- Denominators signal soft and collinear divergences
  - recognise color ordering from <23><41> and <24><31>
  - <12> and <34> are remnants of triple-gluon vertex propagator.

Direct photon amplitude

- Simple prescription to obtain photon amplitudes:
  - replace corresponding color matrix in decomposition with identity matrix
  - change overall coupling

$$\mathcal{M}(\bar{q}_1^+, q_2^-, \gamma_3^-, g_4^+) = ieQ_q g\,(T^{a_4})_{i_2 i_1}\left[M(\bar{q}_1^+, q_2^-, g_3^-, g_4^+) + M(\bar{q}_1^+, q_2^-, g_4^+, g_3^-)\right]$$
$$\equiv ieQ_q g\,(T^{a_4})_{i_2 i_1}\; M(\bar{q}_1^+, q_2^-, \gamma_3^-, g_4^+)\,,$$

- Performing combination analytically is useful:

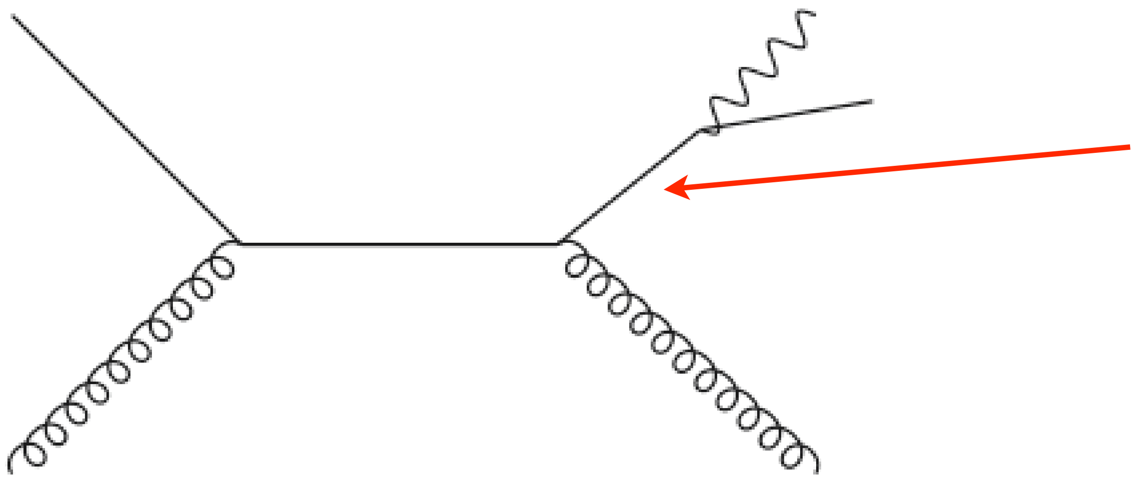
$$M(\bar{q}_1^+, q_2^-, \gamma_3^-, g_4^+) = \frac{\langle 1\,3\rangle\langle 2\,3\rangle^3}{\langle 1\,2\rangle\langle 2\,3\rangle\langle 2\,4\rangle\langle 3\,4\rangle\langle 3\,1\rangle\langle 4\,1\rangle}\left(\langle 2\,4\rangle\langle 3\,1\rangle - \langle 2\,3\rangle\langle 4\,1\rangle\right)$$
$$= \frac{\langle 1\,3\rangle\langle 2\,3\rangle^3}{\langle 2\,3\rangle\langle 2\,4\rangle\langle 3\,1\rangle\langle 4\,1\rangle}\,,$$

Schouten identity:
<ab><cd> = <ac><bd>+<ad><bc>

- As it must, remnant of triple-gluon propagator cancels.
- Form of amplitude identical for 2-photon process.
- Very useful for recycling complicated amplitudes with more jets.

Photons in perturbative QCD

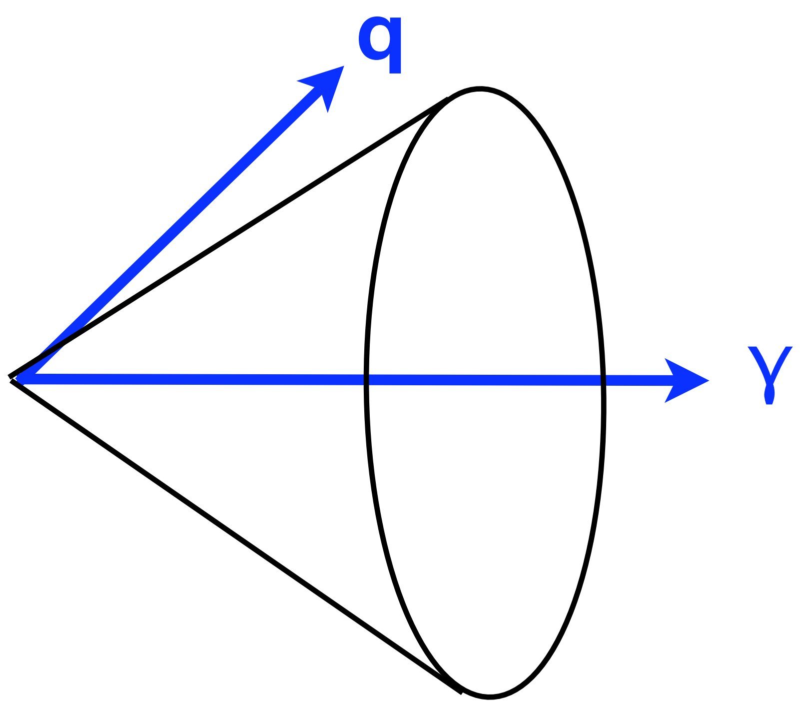
- In the presence of QCD radiation (i.e. beyond LO) the direct photon amplitudes develop additional singularities.



singular propagator when quark and photon are collinear

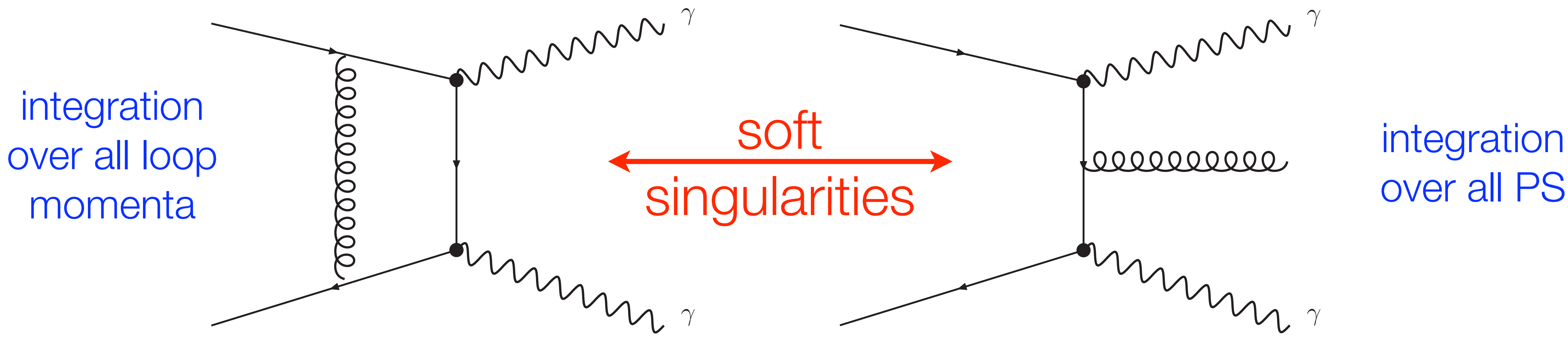
- Naive solution: remove collinear configurations with a cut.

no radiation in "isolation cone"



Cone problems

- Removing quark-photon singularities in this way would be acceptable (but only up to NLO, no all-orders definition like this).
- However, a physically meaningful prediction would also require the same cut on gluons.
- Enforcing such a cut would prohibit the emission of soft gluons inside the cone and be infrared-unsafe: cancellation of virtual/real singularities not complete.



Theorist solution

- Frixione (1998): allow soft partons, but remove collinear configurations.
- Enforced by a cut of the form:

$$\sum_{R_{j\gamma} \in R_0} E_T(\text{had}) < \epsilon_h p_T^\gamma \left(\frac{1 - \cos R_{j\gamma}}{1 - \cos R_0} \right)$$

- Parton required to be softer as it gets closer to photon.
- No contribution exactly at the collinear singularity.
- This is simple to apply to a theoretical calculation and results in a well-defined cross section.
  - with such a cut, higher order calculations with photons no more difficult than corresponding QCD ones
- Cannot be (exactly) implemented experimentally due to finite detector resolution.
  - could tweak parameters of the cut (ε_h, R_0) for good agreement with experimental data (ideally, universally)

Conventional approach

- Usually, isolation cone allows a small amount of hadronic energy inside.

$$\sum_{\in R_0} E_T(\text{had}) < \epsilon_h \, p_T^\gamma \qquad \text{or} \qquad \sum_{\in R_0} E_T(\text{had}) < E_T^{\text{max}}$$

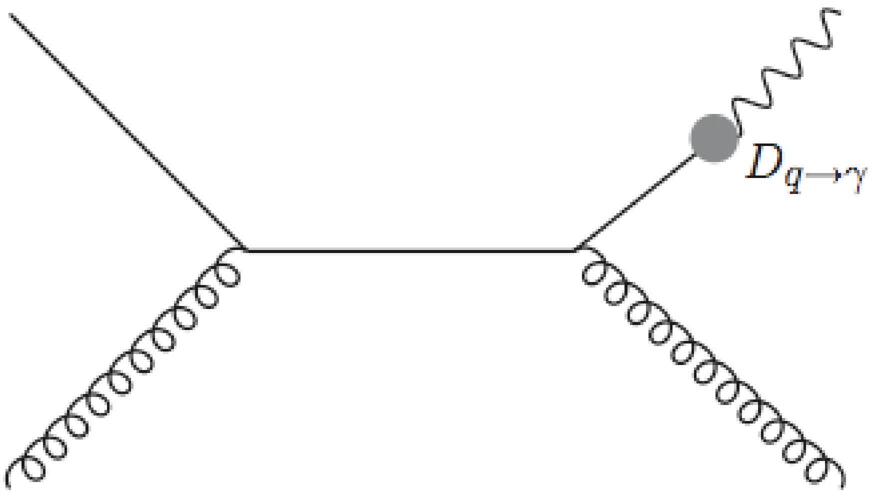
- Okay for QCD infrared-safety, but collinear quark-photon singularity again exposed.
- Singularities can be handled by usual higher-order machinery, e.g. dipole subtraction, and exposed:

$$-\frac{1}{\epsilon}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{4\pi\mu^2}{M_F^2}\right)\frac{\alpha}{2\pi}\, e_q^2 P_{\gamma q}(z)$$

- Just like initial-state collinear singularities are absorbed into pdfs, these can be defined away.

Photon fragmentation

- The analogous quantity to pdfs is the photon fragmentation function: defined for each flavour of parton.
- Inclusion of fragmentation function introduces an additional scale to the problem: fragmentation scale, M_F.



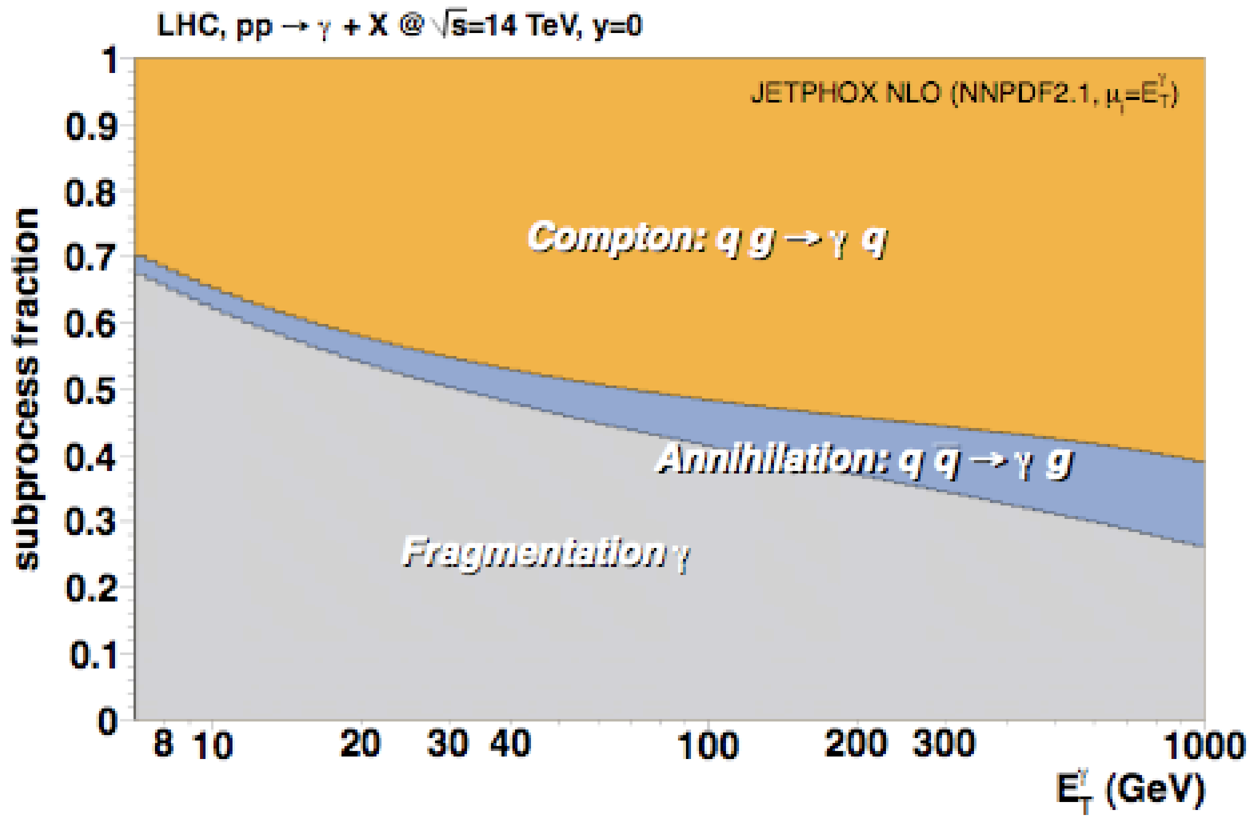
- Just like pdfs: non-perturbative input required, but perturbative evolution. Defined order-by-order in pQCD.
- Using conventional isolation, cross-section now has two components:

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\gamma+X}(M_F) + \sum_i \mathrm{d}\sigma_{i+X} \otimes D_{i\to\gamma}(M_F)$$

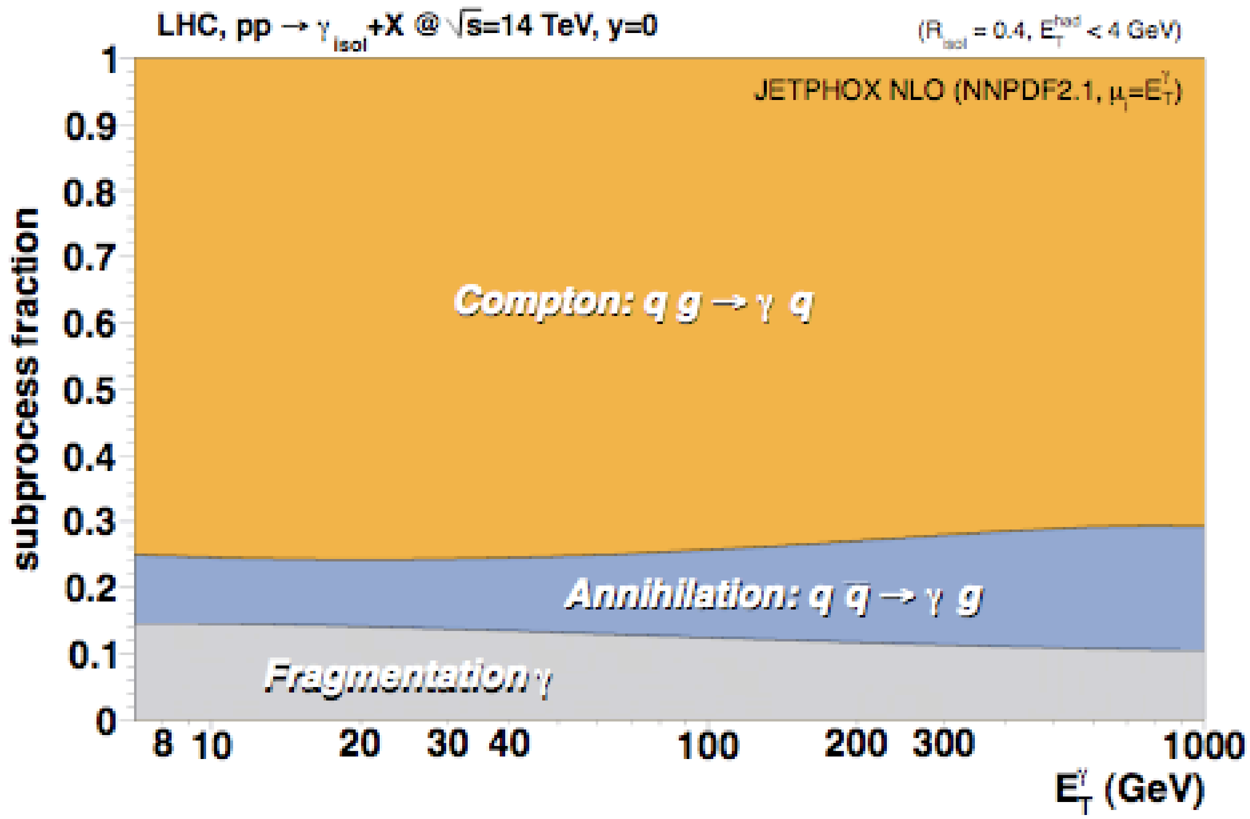
direct/prompt — fragmentation

  - separation well-defined only for a given M_F.
- After isolation, the finite remainder from the fragmentation contribution is typically small.

Size of contributions



inclusive

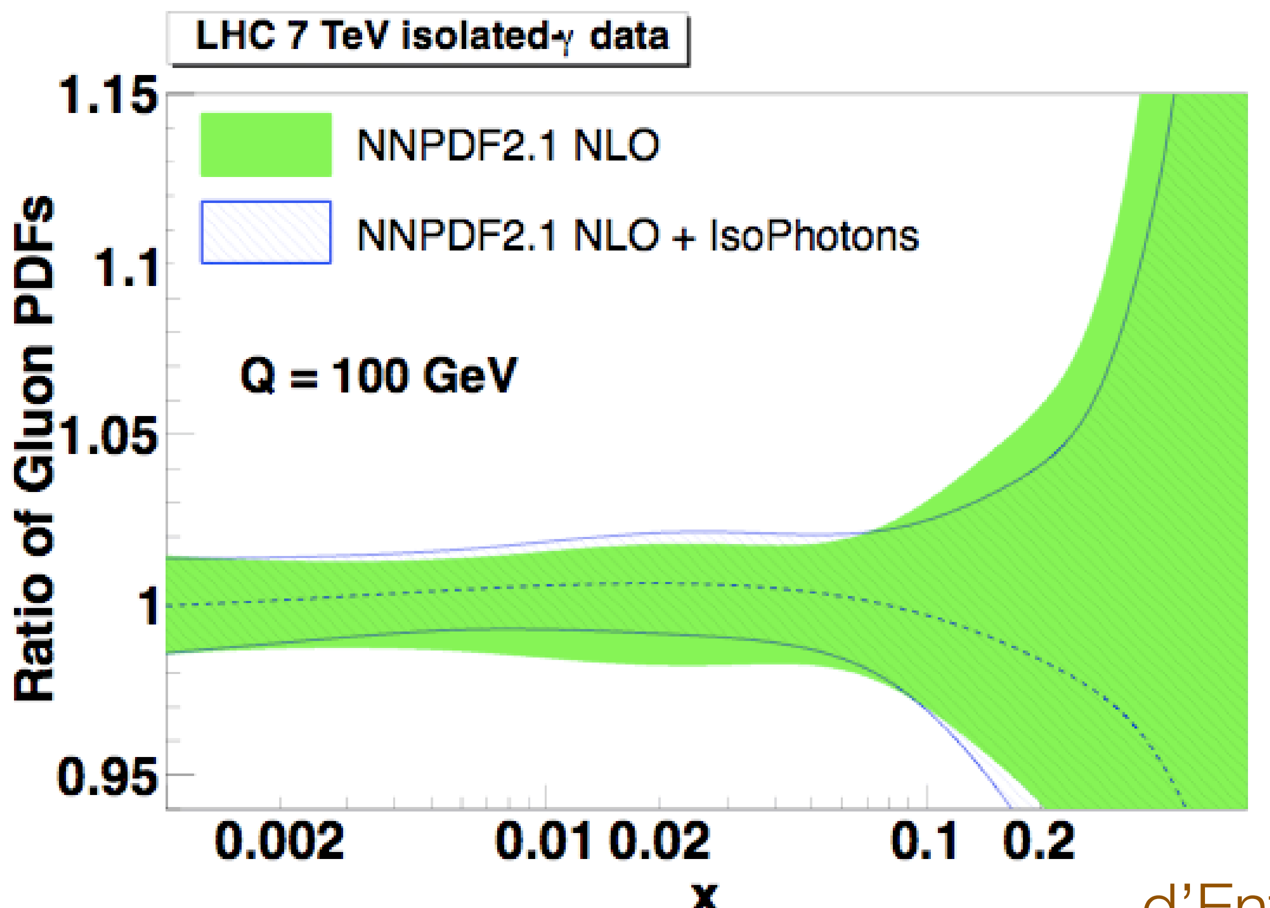


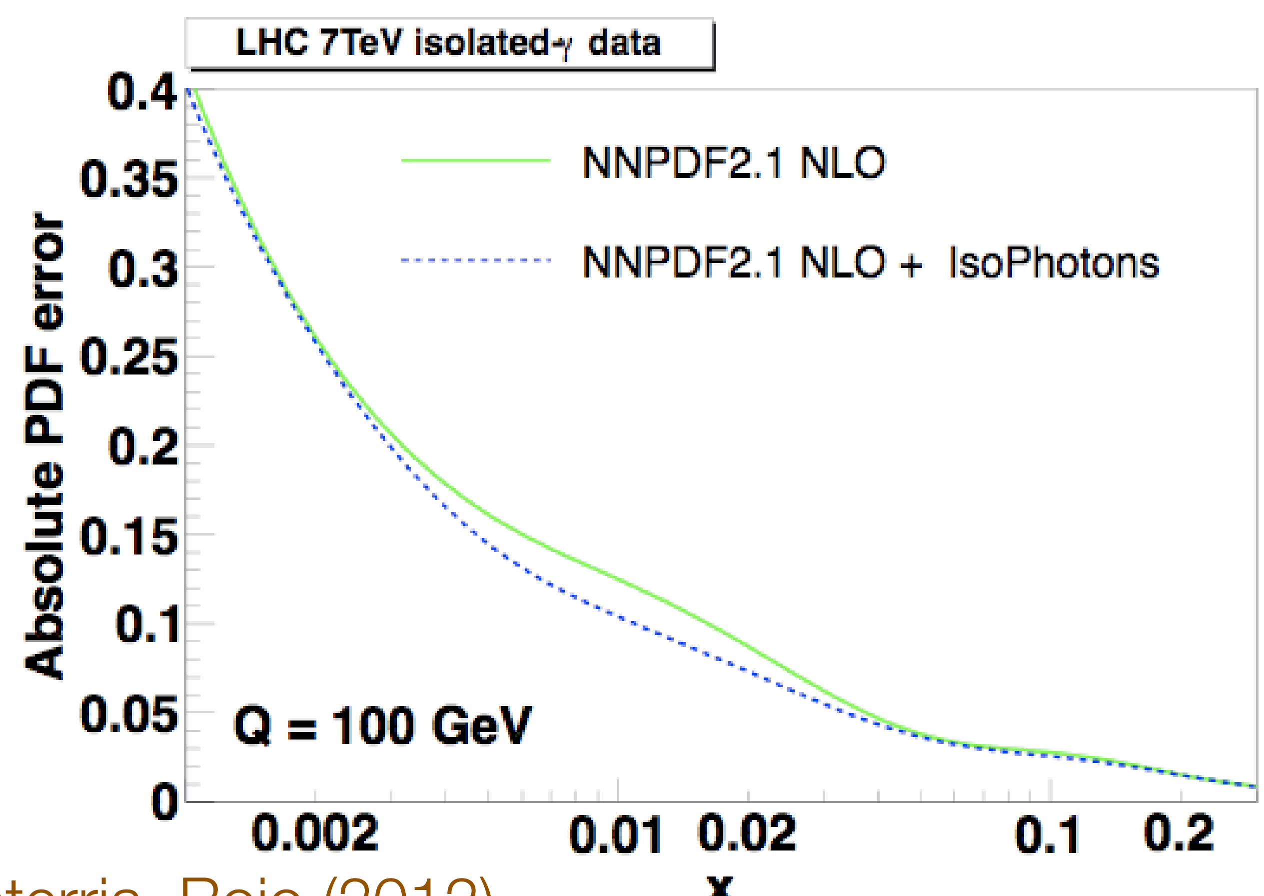
isolated photon

- Direct photon production at NLO in MCFM and JETPHOX (shown here).
- In the inclusive case fragmentation contribution is large, even at high p_T.
- After isolation, both fragmentation and annihilation contributions small.
  - this process is therefore domination by the Compton mode and thus can potentially provide a useful probe of gluon pdf.

Pdf improvements from direct photons

- Study using NNPDF with up to 7 TeV LHC data only
  - shows slight improvement in gluon uncertainty
  - potential for improvement with more data, subject to some caveats: only NLO (NNLO becoming the standard), non-perturbative corrections need to be better-understood.

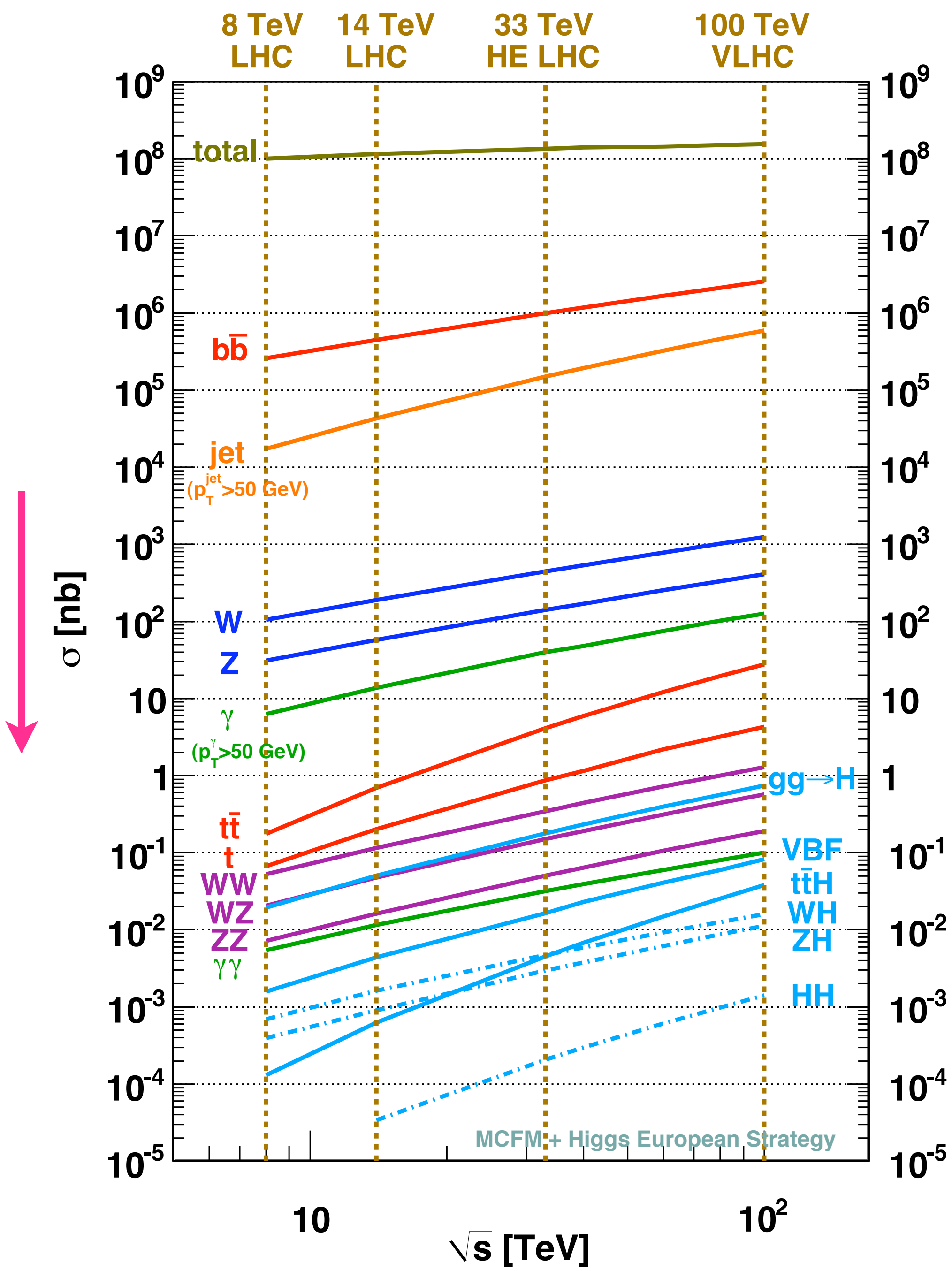




d'Enterria, Rojo (2012)

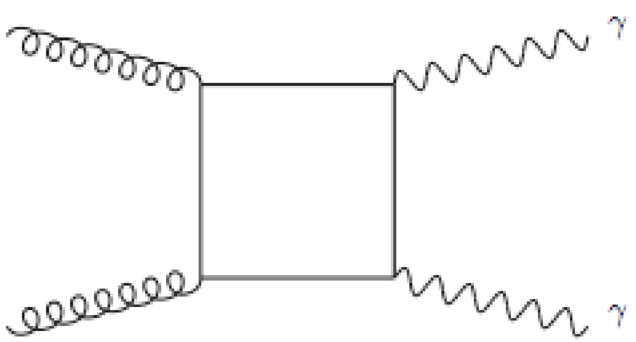
Di-photon production

- Clear interest as the principal background to the Higgs process, gg→H→γγ.
    - even though the background is subtracted with a fitting procedure, we should also have some control of this process ab initio.
- Experimentally, significant contamination of this partonic process from the production of jets, or photon+jet, where jets are mis-identified as photons.
    - the cross-sections for these strong processes are so much larger that mis-identification rates as small as 10^{-4} must be handled with care.
- Here, just focus on a few aspects of the true partonic process: $q\bar{q} \rightarrow \gamma\gamma$



Higher order corrections

- NLO corrections included in DIPHOX and MCFM.
- A particular class of NNLO contributions is separately gauge-invariant and numerically important at the LHC due to the large gluon flux:



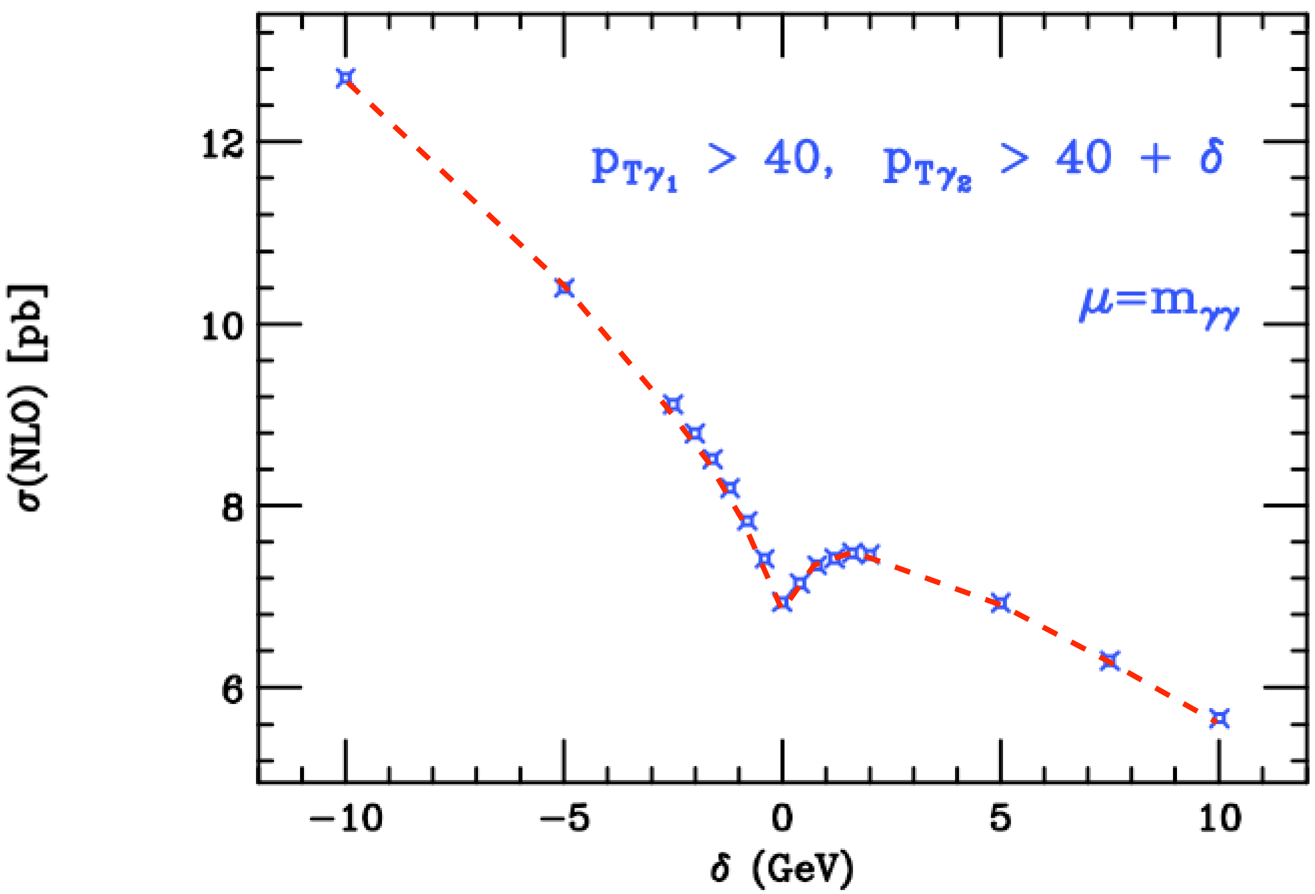
Since there is no tree level ggγγ coupling, this loop contribution is finite
→ can add separately.

(in fact, finite nature means that one can compute corrections to it, i.e. part of N^3LO, using just NLO technology)

- Contributes approximately 15-25% of the NLO total, depending on exact choice of photon cuts, scale choice, etc.
- Interesting behaviour of perturbative calculation in the case of photon cuts favoured by the experiment - “staggered” p_T cuts where second photon not required to be as hard as first
    - useful for purity of the signal or rejection of fake backgrounds

Staggered photon cuts

- Consider typical cuts of the form: $p_T^{\gamma_1} > 40\ \text{GeV}\ , \qquad p_T^{\gamma_2} > 40 + \delta\ \text{GeV}$
- Exposes a weakness in the pertubative calculation because at leading order photons are produced back-to-back with equal p_T
  - sensitivity to staggered cut only begins at NLO.



Rather sensitive to value of δ, NLO correction becomes very large if cuts are too far apart.

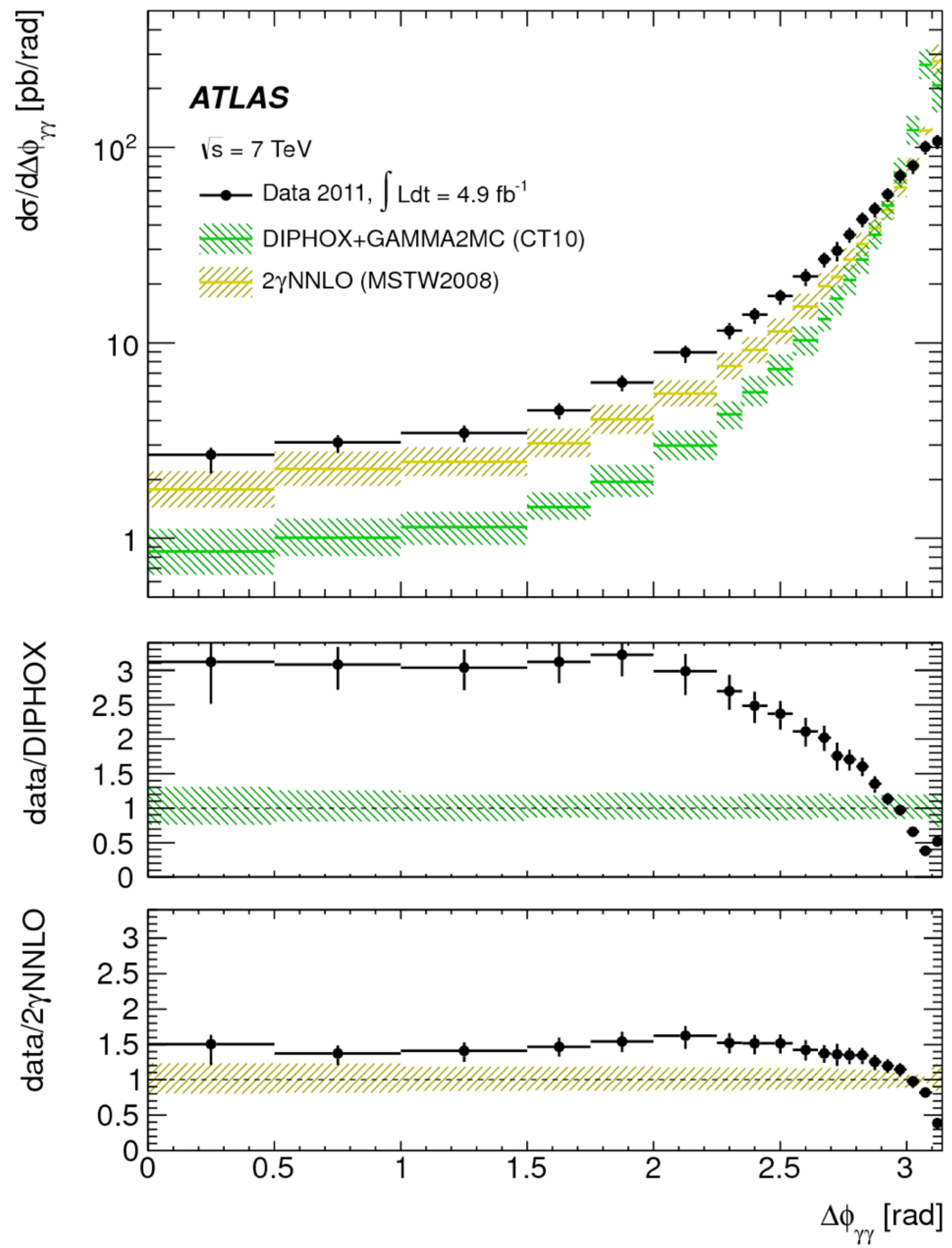
Cusp at δ=0 due to emission of soft gluons and presence of δ log δ enhancement (candidate for resummation).

Frixione, Ridolfi (1997)

Lesson: perturbative stability in the threshold region requires "moderate" δ.

NNLO results

- A full NNLO calculation has recently been performed, in the "Frixione" scheme, i.e. no need for fragmentation contributions.
  Catani et al (2012)
- Better description of kinematic regions that are poorly described or inaccessible at NLO.
- Good example: azimuthal angle between photons only non-trivial at NLO in the total cross-section.
- Even better description would require either higher orders or inclusion in parton shower → not yet feasible.



Summary

- Overview of vector boson basics.
  - importance, Feynman rules, decays
- Underlying theory of W,Z production.
  - NNLO QCD, NLO EW, DLLA, resummation, W/Z+jets
- Discussion of the direct photon process.
  - isolation, fragmentation, sensitivity to pdfs
- Di-photon production.
  - subtleties of higher orders in pQCD.