Vector bosons and direct photons

Lecture 1

CTEQ school 2013

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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.

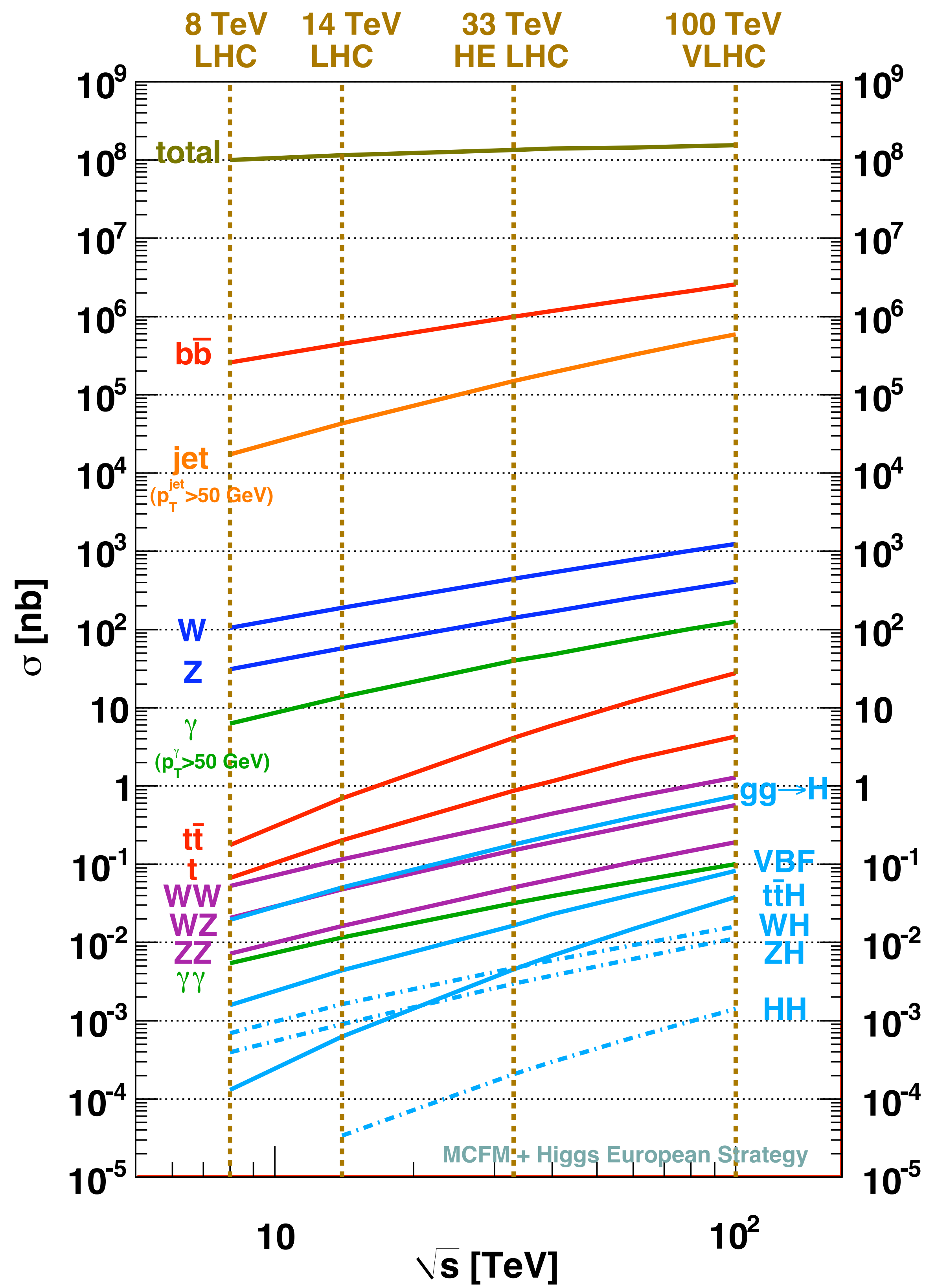
Outline of lectures

- 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:

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

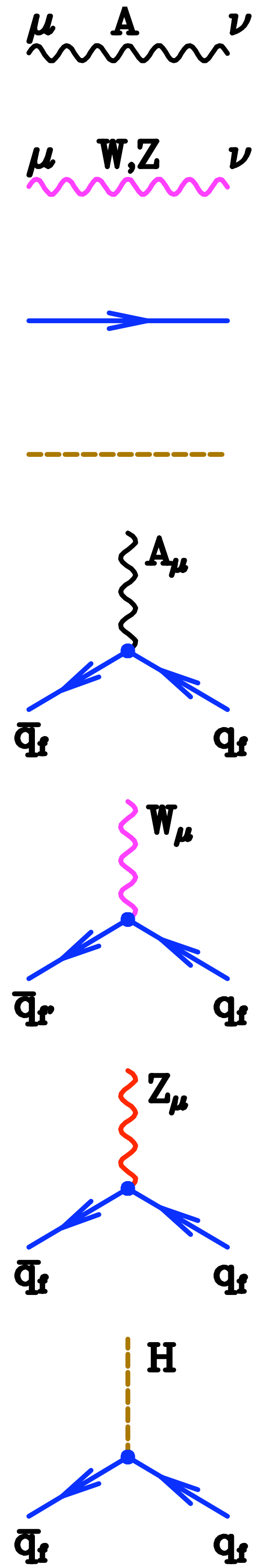
- W boson couples to left-handed fermions
- Z boson couples to both, different strengths:

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

  - vector and axial couplings in terms of weak isospin $T^3_f = \pm½$

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

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



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

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

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

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

$$-ieQ_f\gamma_\mu$$

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

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

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

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

W and Z decays

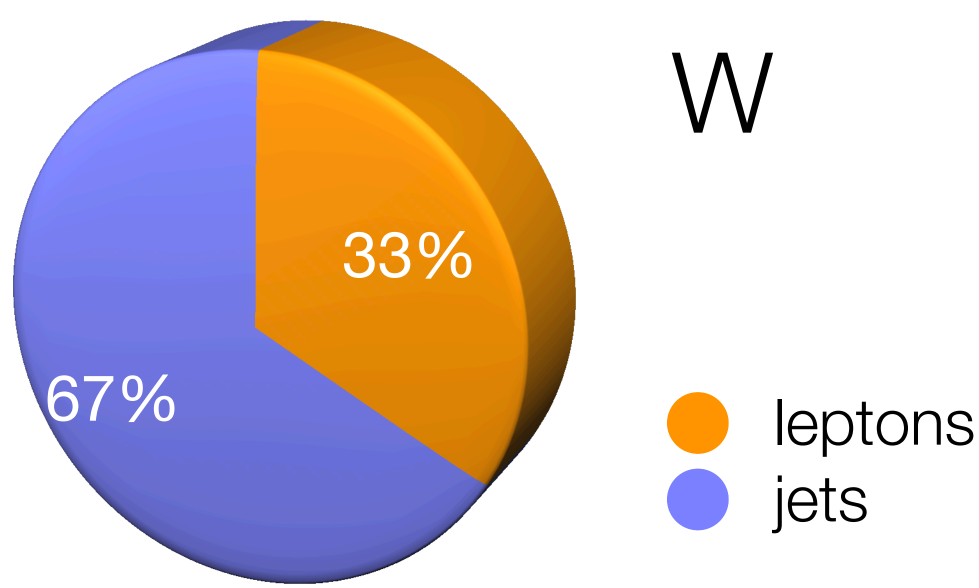
- Partial decay widths at leading order:

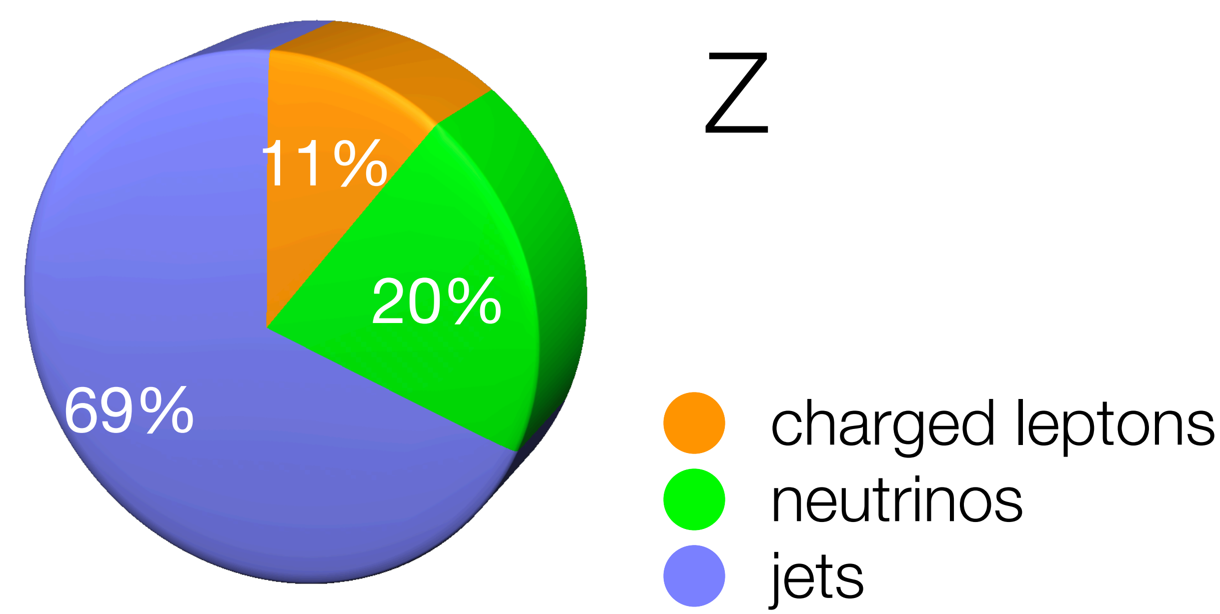
$$\Gamma(W^+ \to f\bar{f}') = C\,\frac{G_F M_W^3}{6\sqrt{2}\pi} \qquad \Gamma(Z \to f\bar{f}) = C\,\frac{G_F M_Z^3}{6\sqrt{2}\pi}\left(V_f^2 + A_f^2\right)$$

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 x Br($Z \to e^+e^-$)





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

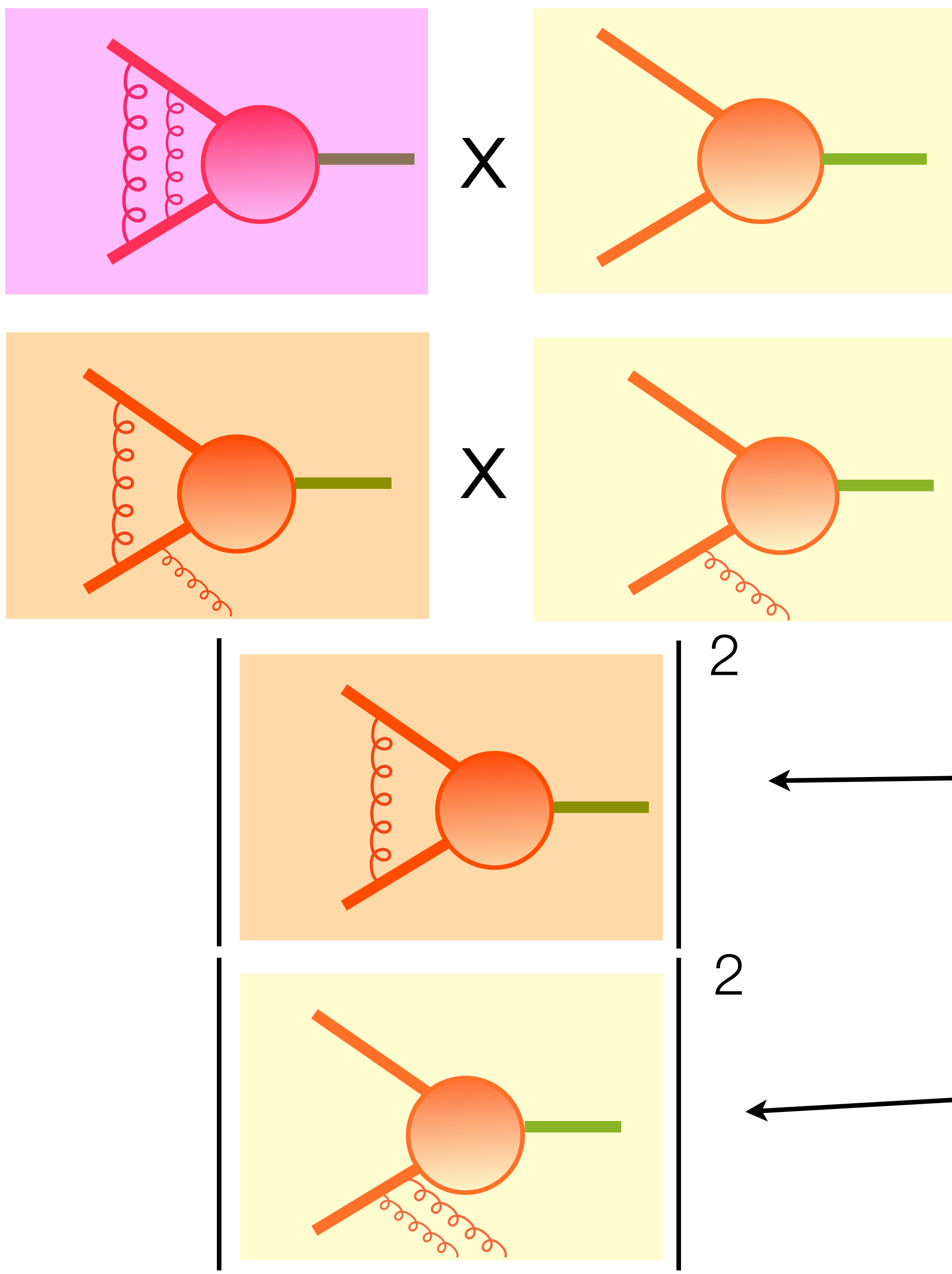
W and Z production

- 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.

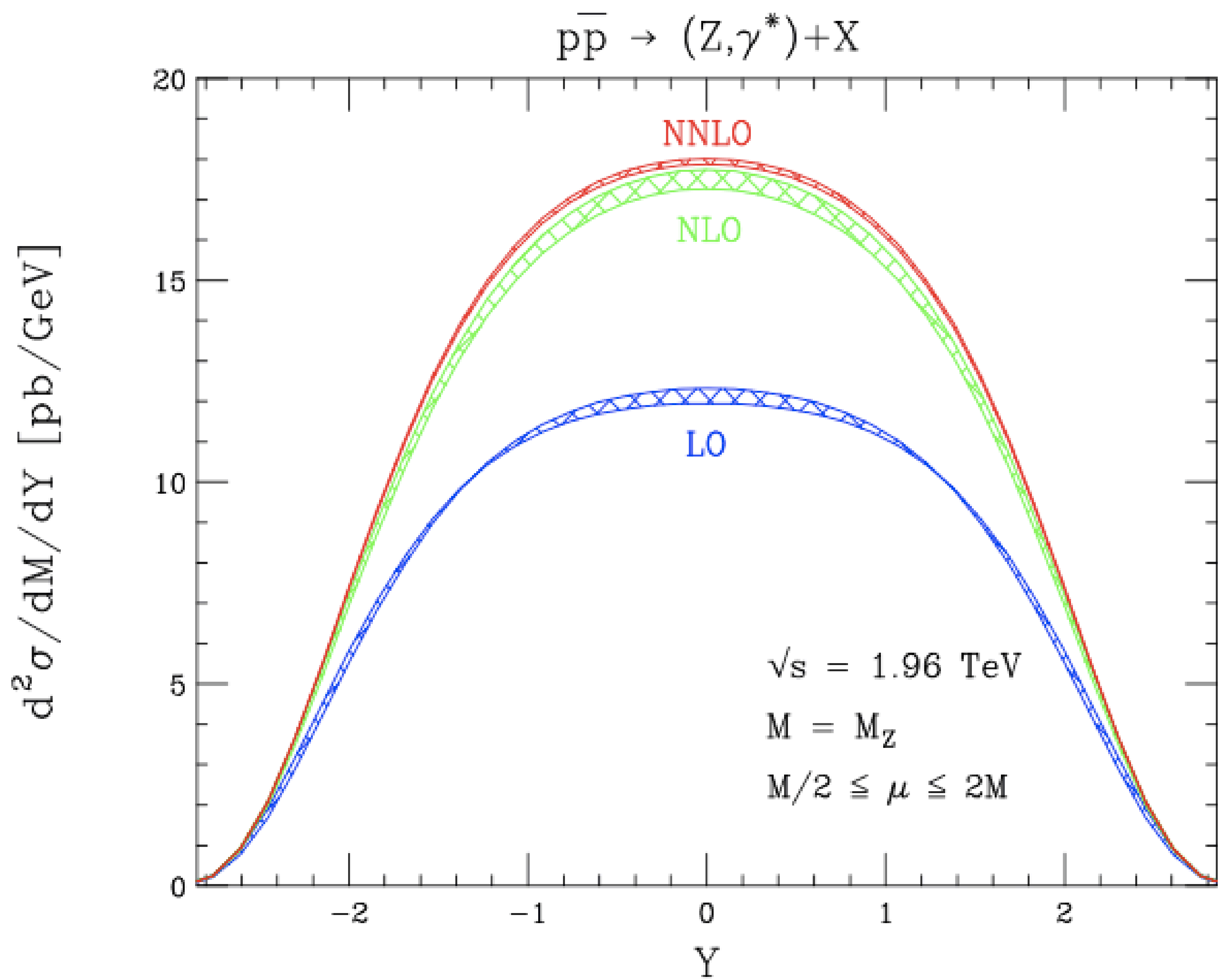


needs 2-loop amplitude, for many years the unknown ingredient

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



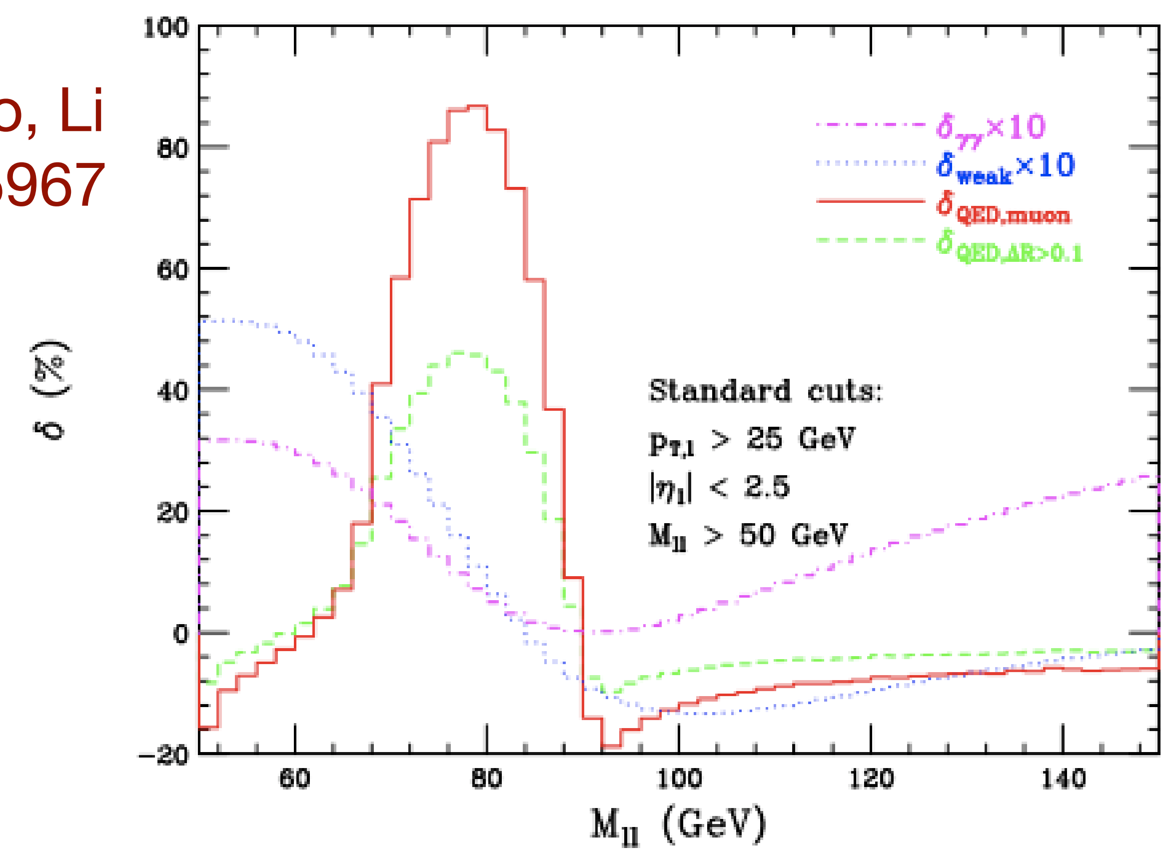
Anastasiou, Dixon, Melnikov, Petriello (2004)

- 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.
- Especially important near the Z peak.
- Sensitivity to the definition of the lepton ("bare" or "dressed", recombined with photon).
- Should include photon-induced contributions $\gamma\gamma \rightarrow \ell^+\ell^-$.
- Open issue: how to combine QCD and QED contributions.

Petriello, Li
1208.5967

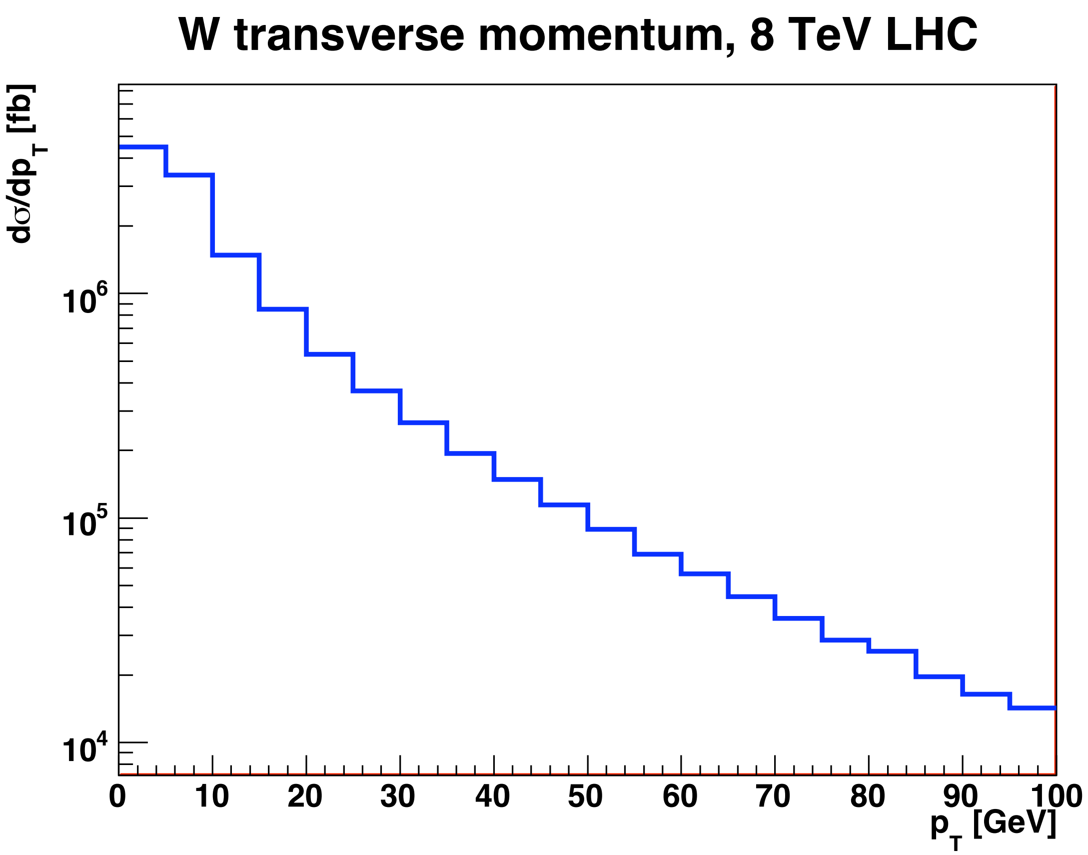


A different approach

- 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.
    - 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.



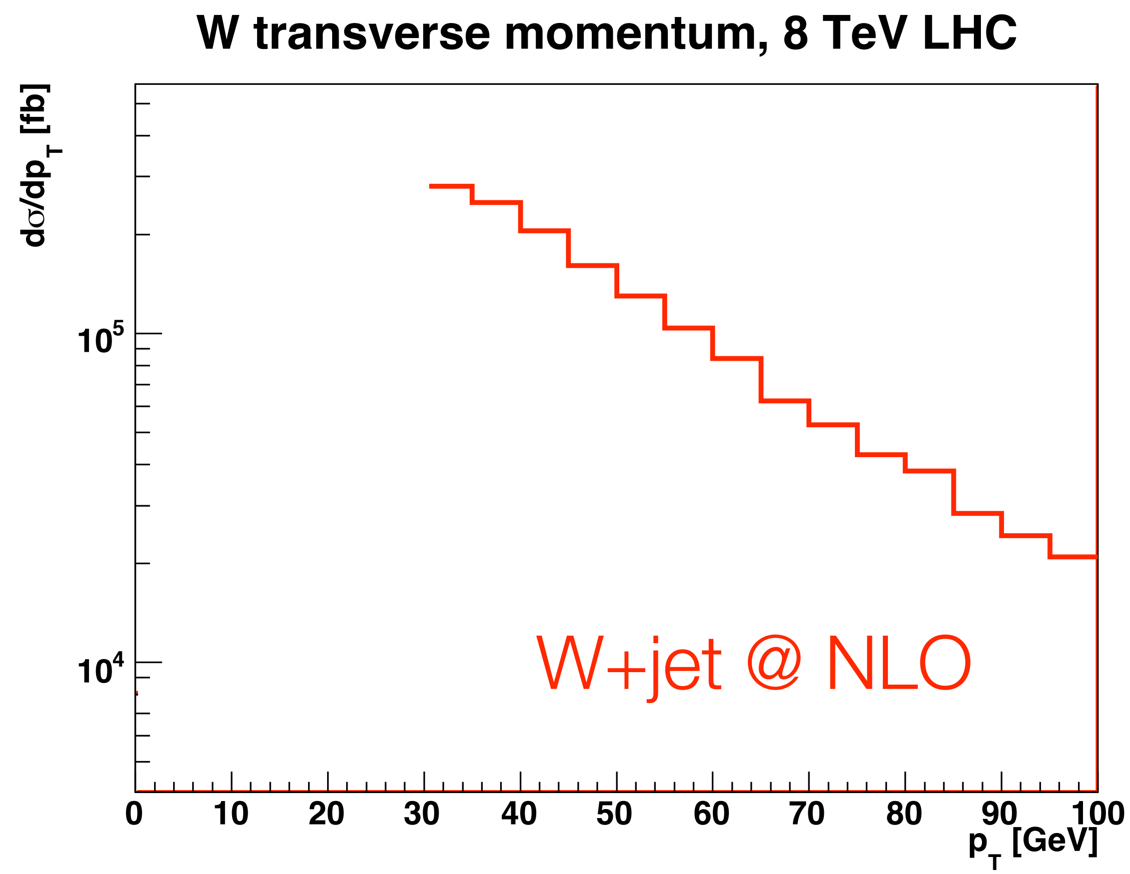
One approach

- 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,

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

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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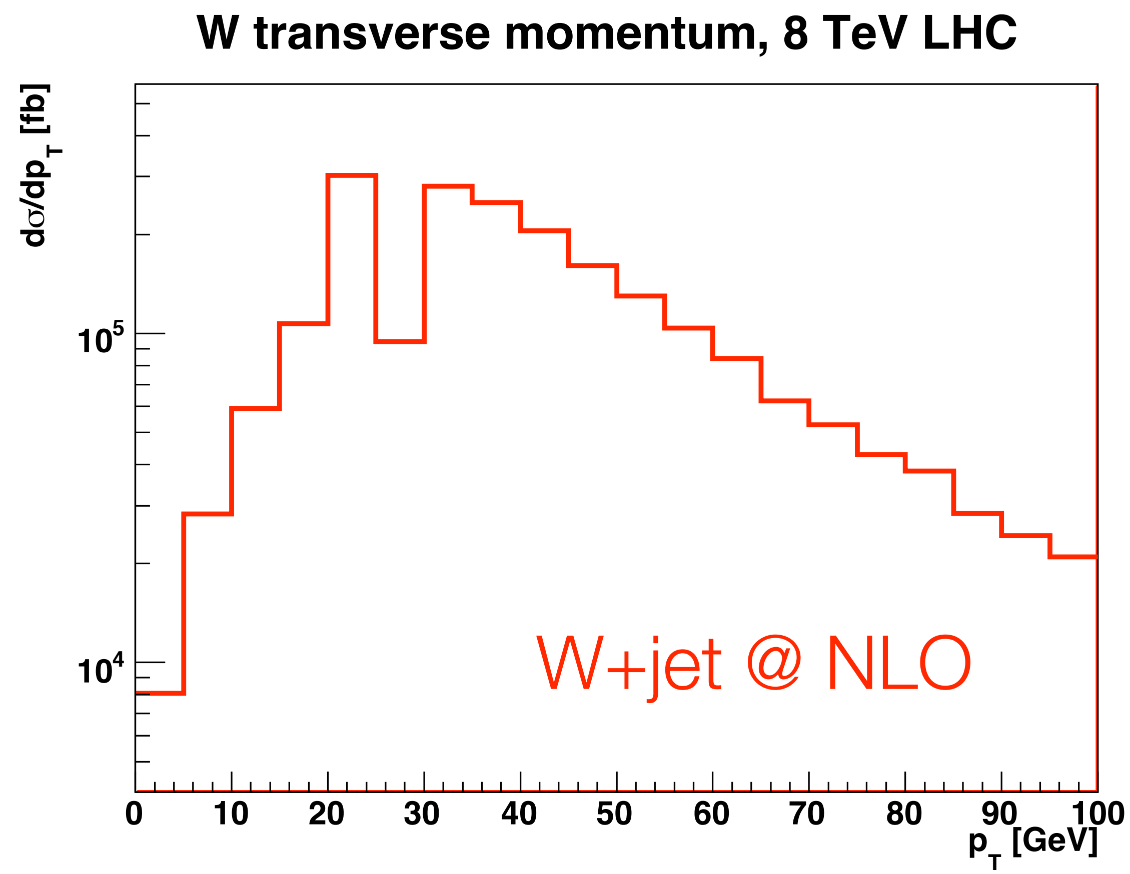
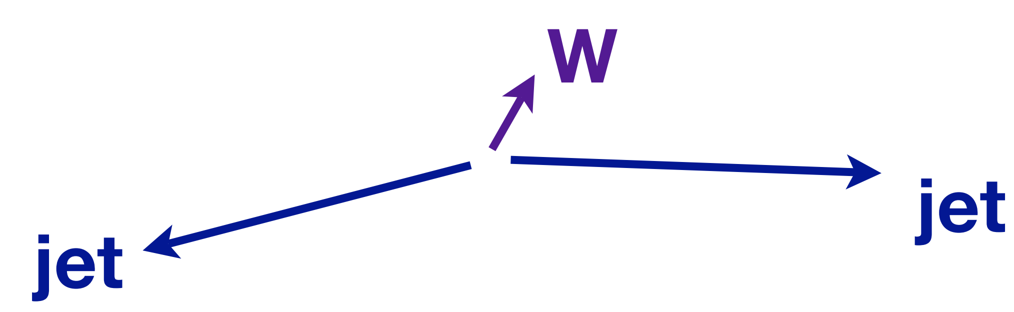


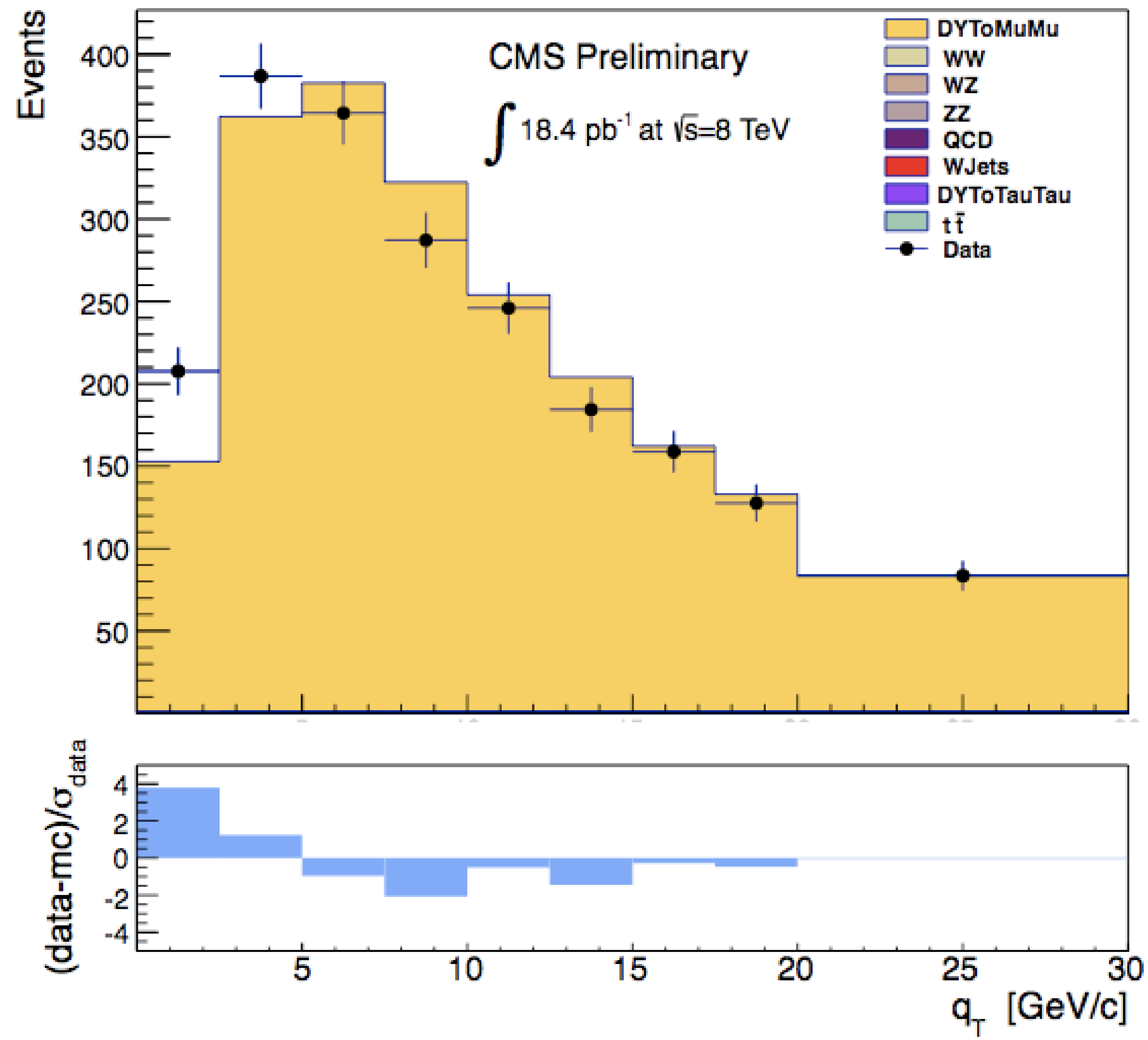
- Below the jet cut, W p_T is populated by configurations with two almost-balancing jets → LO only.



- 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.

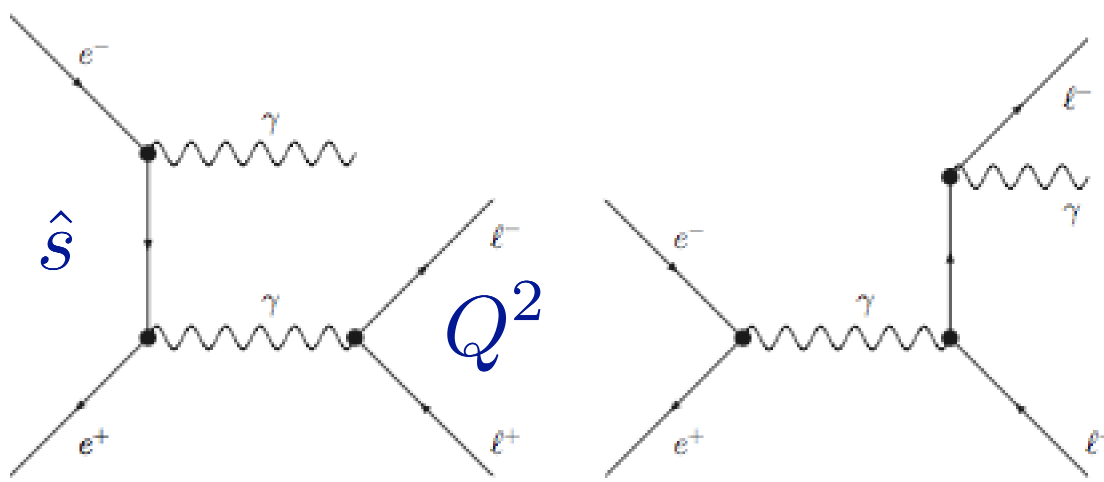


Introduction to resummation

- 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).



Form of doubly-differential cross section at small Q_T:

$$\frac{d\hat{\sigma}_R}{dQ_\perp^2\, dQ^2} = \frac{4\alpha^2}{3\hat{s}}\, \frac{\alpha}{\pi Q_\perp^2 Q^2}\, \frac{\hat{s}^2 + Q^4}{\hat{s} - Q^2} = \hat{\sigma}_0\, \frac{\alpha}{\pi Q_\perp^2 Q^2}\, \frac{\hat{s}^2 + Q^4}{\hat{s} - Q^2}$$

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

- Integrate over Q^2 close to partonic threshold: $s(1-\delta) \leq Q^2 \leq s - Q_T^2$

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

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

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:

$$\int_0^{p_\perp^2} (\mathrm{d}\hat{\sigma}_R + \mathrm{d}\hat{\sigma}_V) = \sigma_0 \left(1 - \frac{\alpha}{\pi} \int_{p_\perp^2}^{\hat{s}} \frac{\mathrm{d}Q_\perp^2}{Q_\perp^2} \log \frac{\hat{s}}{Q_\perp^2}\right)$$
$$= \sigma_0 \left(1 - \frac{\alpha}{2\pi} \log^2 \frac{\hat{s}}{p_\perp^2}\right)$$

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: $\sigma_0\left(1+\epsilon^{(1)}\right) \equiv \sigma_0\left(1-\frac{\alpha}{2\pi}\log^2\frac{\hat{s}}{p_\perp^2}\right)$
- 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:

$$\Sigma(p_\perp^2) \equiv \sigma_0 \sum_{n=0}^{\infty} \epsilon^{(n)} = \sigma_0 \sum_{n=0}^{\infty} \frac{1}{n!}\left(-\frac{\alpha}{2\pi}\log^2\frac{\hat{s}}{p_\perp^2}\right)^n = \sigma_0 \exp\left(-\frac{\alpha}{2\pi}\log^2\frac{\hat{s}}{p_\perp^2}\right)$$

Sudakov form factor: no emissions harder than p_T

- Recover differential distribution by taking derivative:

$$\frac{\mathrm{d}\Sigma(p_\perp^2)}{\mathrm{d}p_\perp^2} = \sigma_0\,\frac{\alpha}{\pi}\left(\frac{1}{p_\perp^2}\log\frac{\hat{s}}{p_\perp^2}\right)\exp\left(-\frac{\alpha}{2\pi}\log^2\frac{\hat{s}}{p_\perp^2}\right)$$

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

Comments

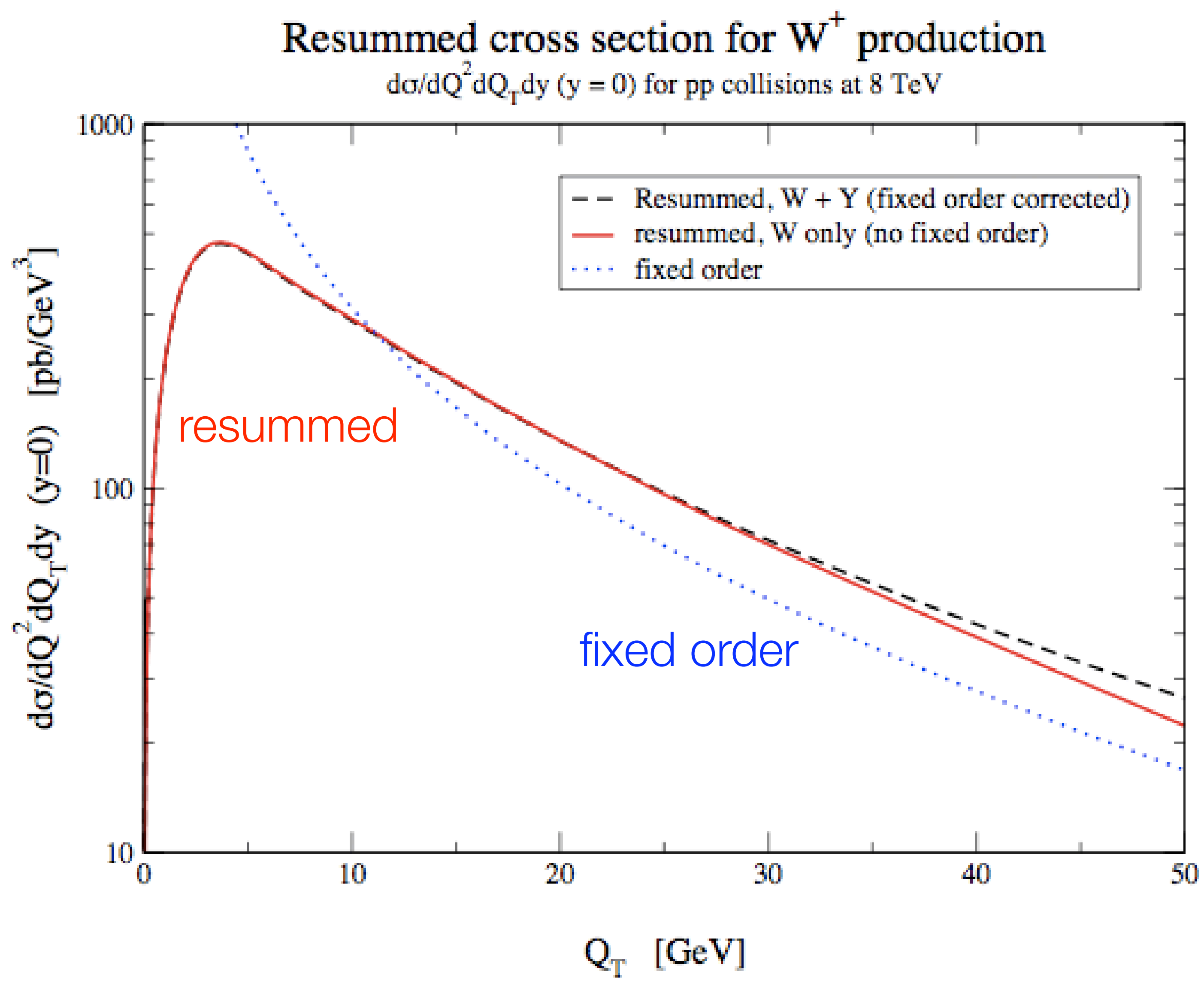
- This is far from the end of the story:
  - although there is no divergence, the cross section is now too suppressed.
  - the behaviour is modified by sub-leading logarithms.
  - the treatment of multiple emission is also over-simplified, since emissions are all considered independent with no accounting 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
  - "Collins-Soper-Sterman" resummation formalism, as implemented in RESBOS code.

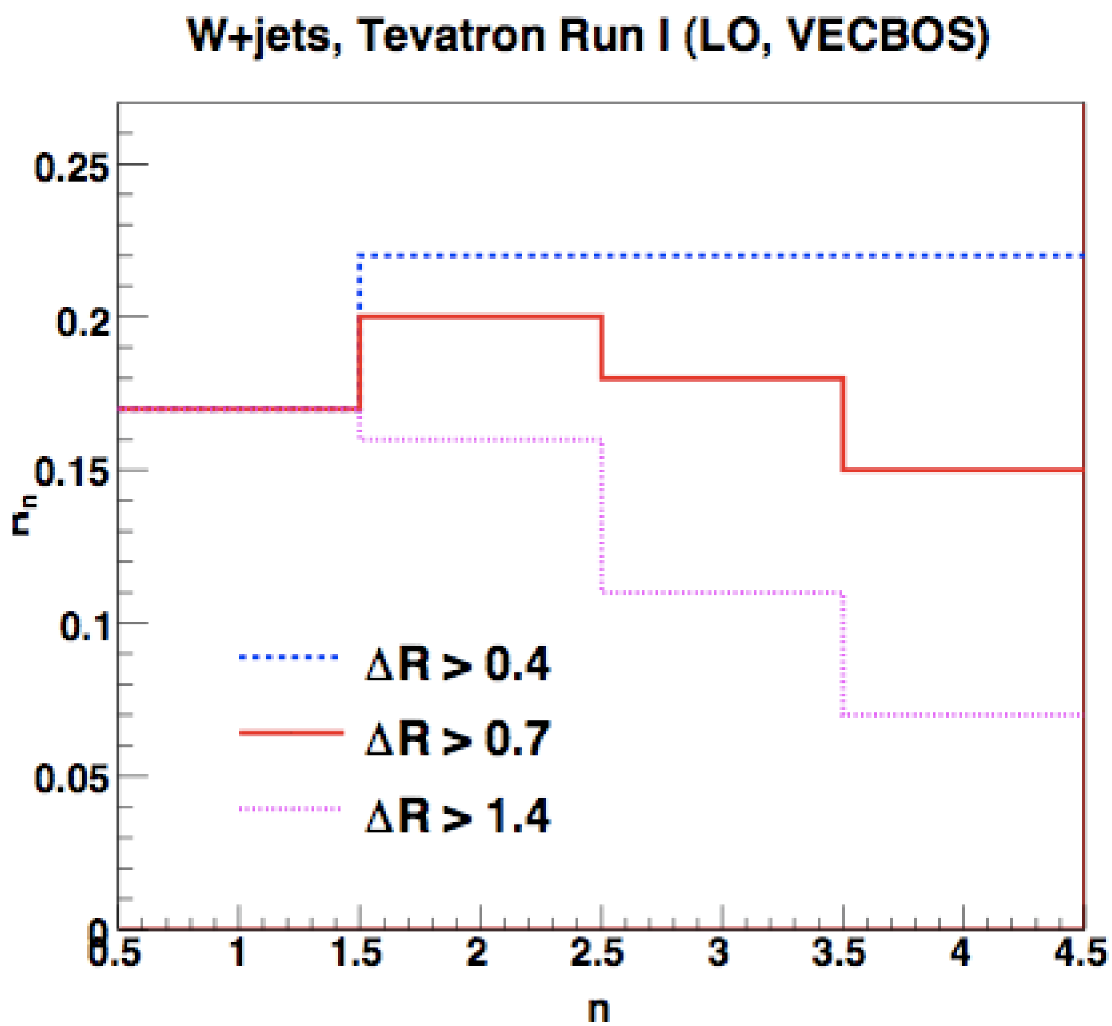


W,Z + jets

- 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.

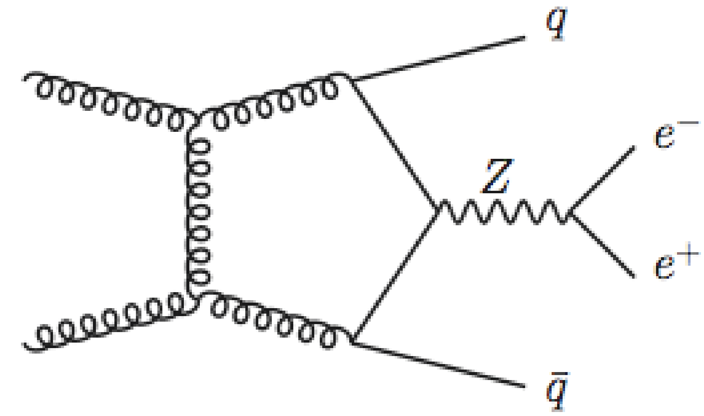


Similar recursive techniques now used in ALPGEN, SHERPA, Madgraph

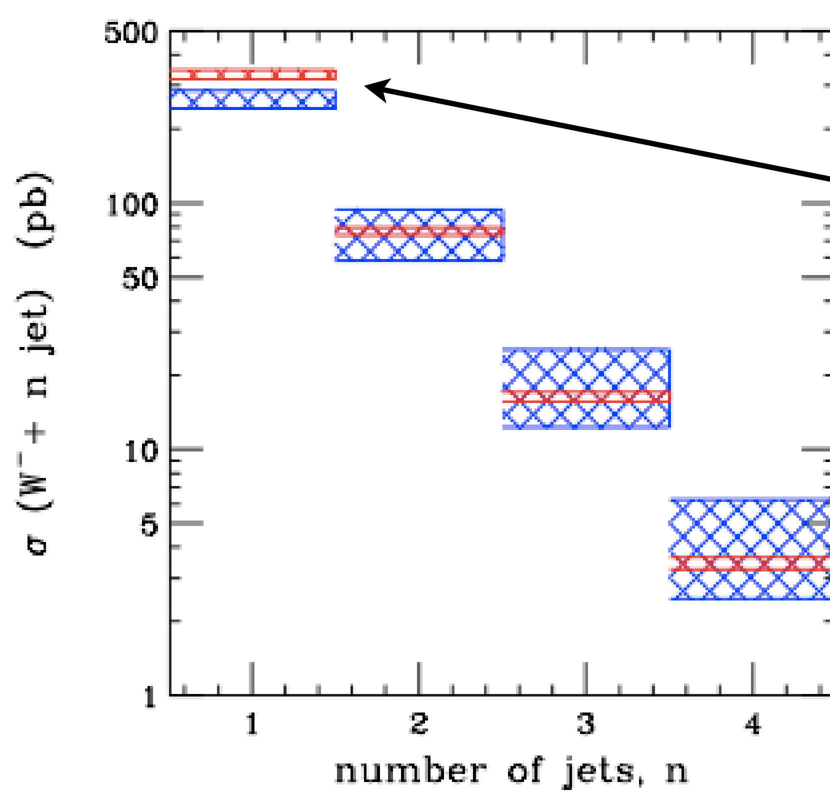
Useful observation about the scaling of the cross section with additional jets:

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

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.

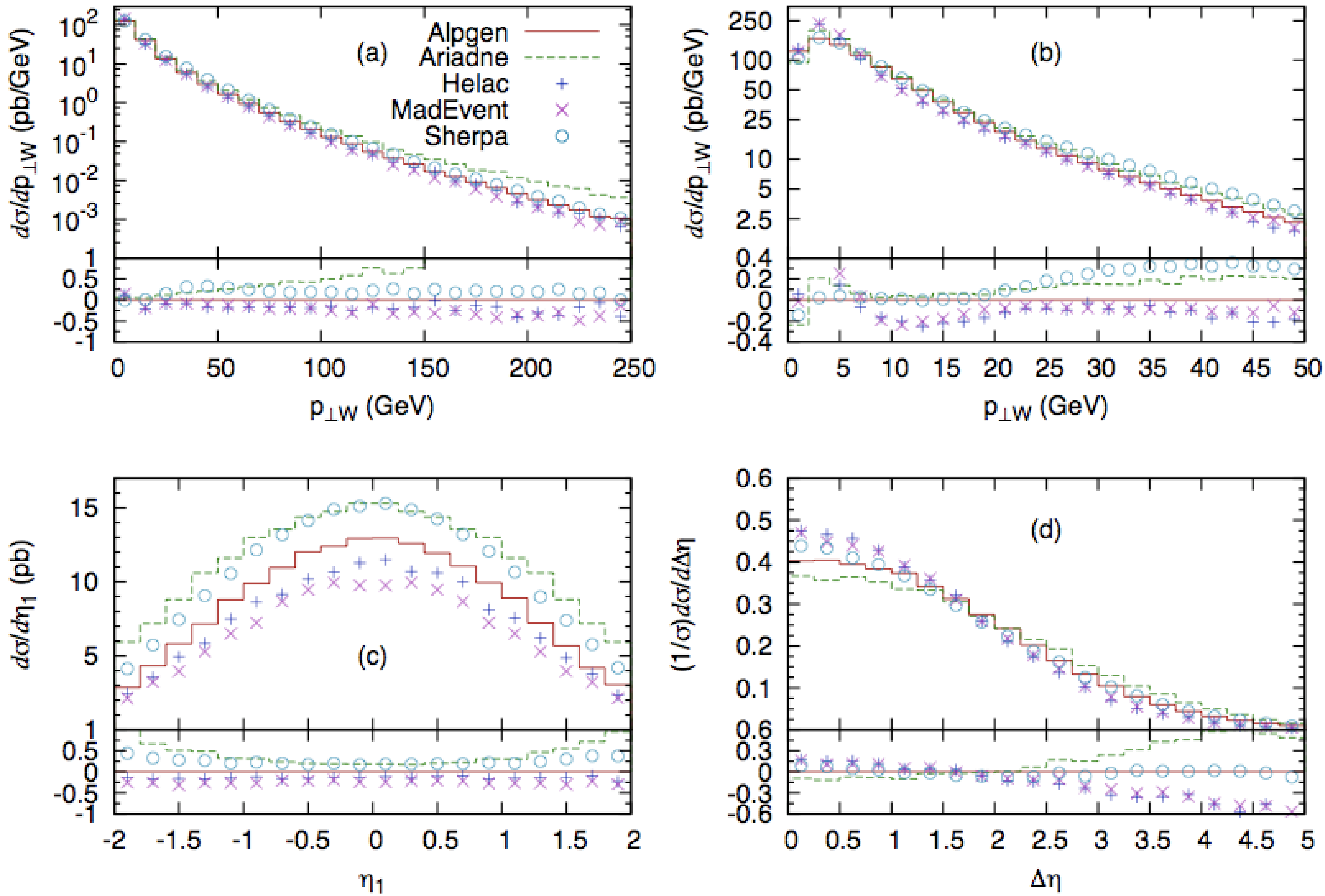


note unusual behaviour for V+1 jet; caused by inclusion of the effect of incident gluons for the first time at NLO

Improved parton showers

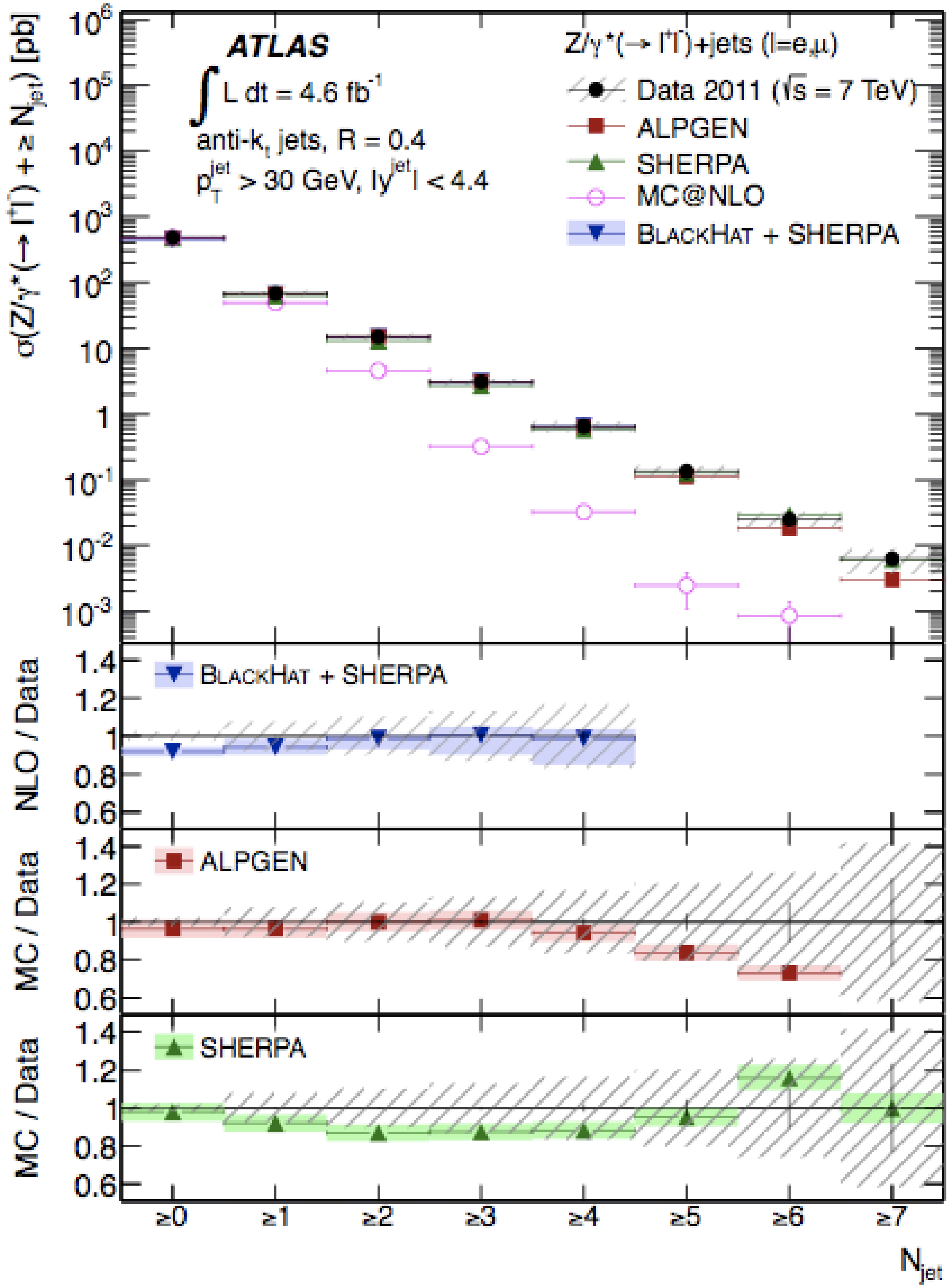
- Test bed for merging schemes at LO.

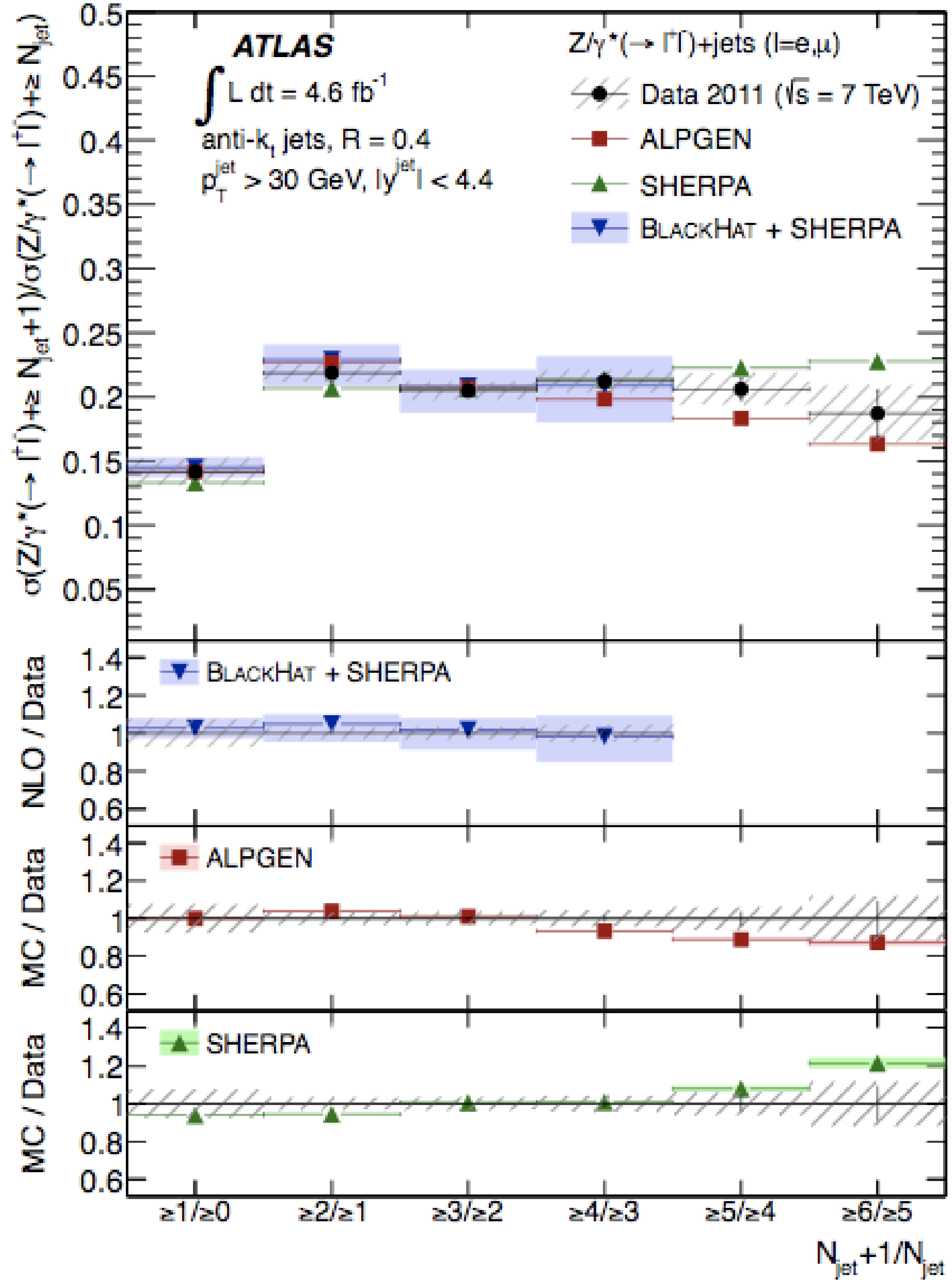
Alwall et al (2007)



Recent comparison with data

CERN-PH-EP-2013-023

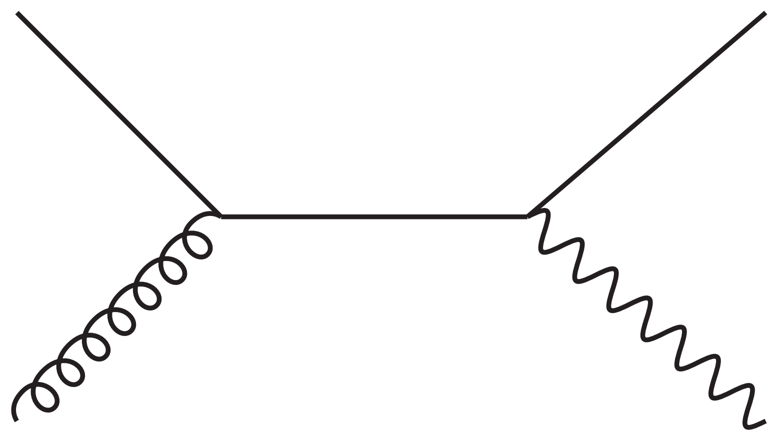


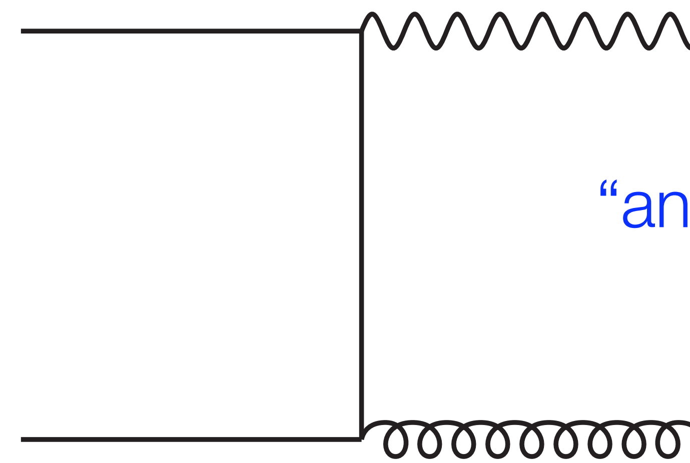


Direct photon production

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

“Compton”



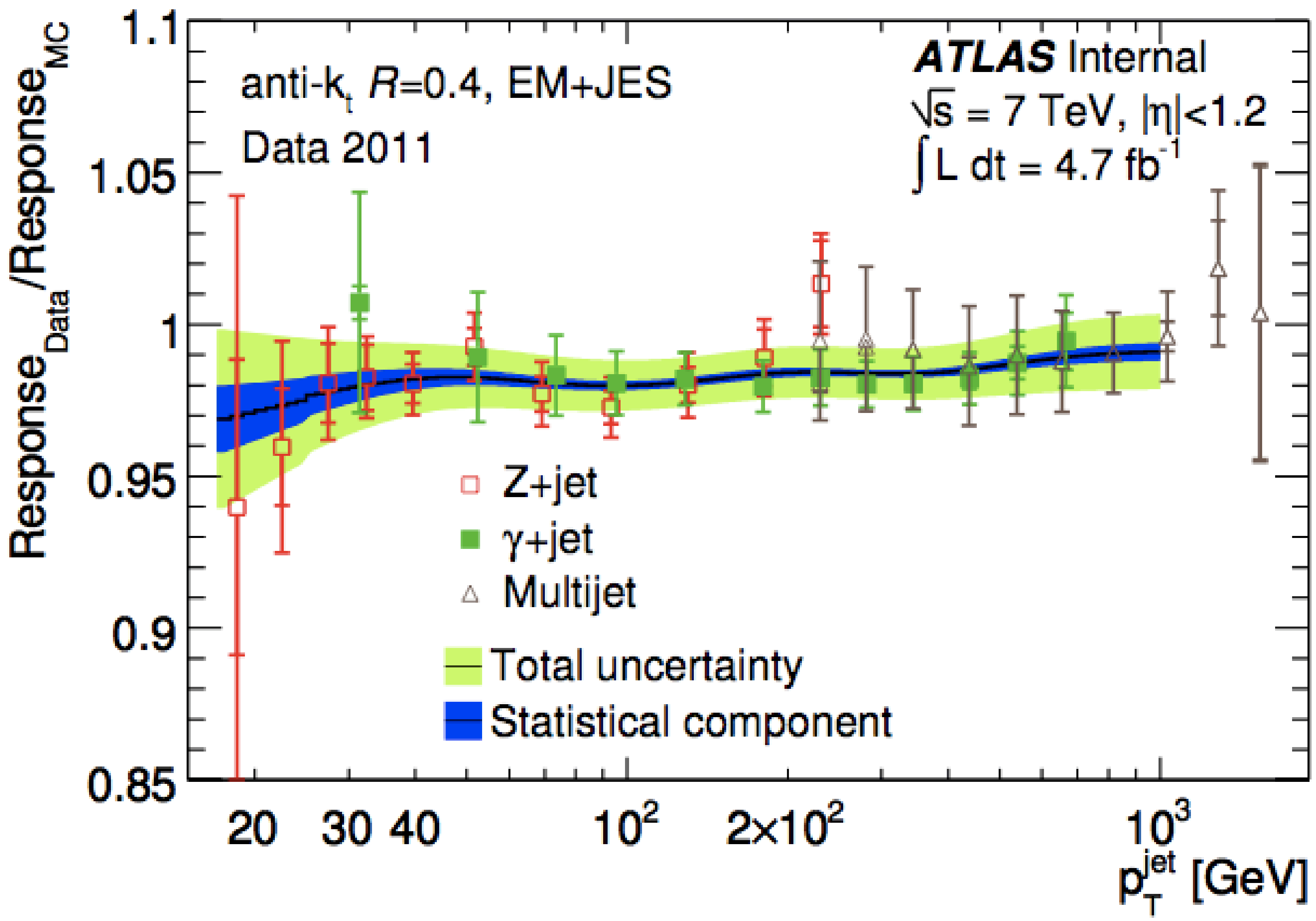


“annihilation”

- 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(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>
  - <34> is remnant 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

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

- Performing combination analytically is useful:

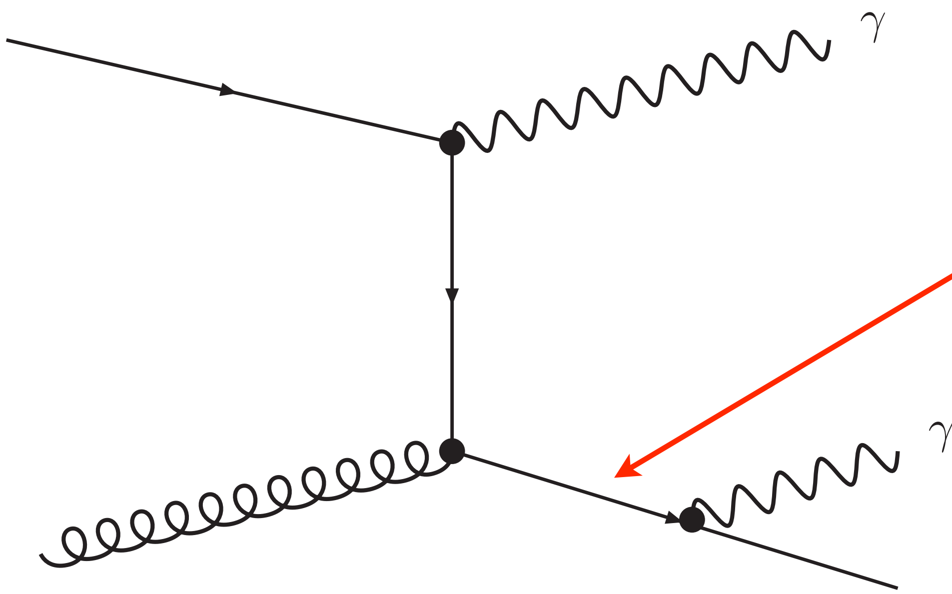
$$\begin{aligned}M(\bar{q}_1^+, q_2^-, \gamma_3^-, g_4^+) &= \frac{\langle 1\,3\rangle\langle 2\,3\rangle^3}{\langle 1\,2\rangle\langle 2\,3\rangle\langle 2\,4\rangle\langle 3\,4\rangle\langle 3\,1\rangle\langle 4\,1\rangle}\left(\langle 2\,4\rangle\langle 3\,1\rangle - \langle 2\,3\rangle\langle 4\,1\rangle\right)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

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.

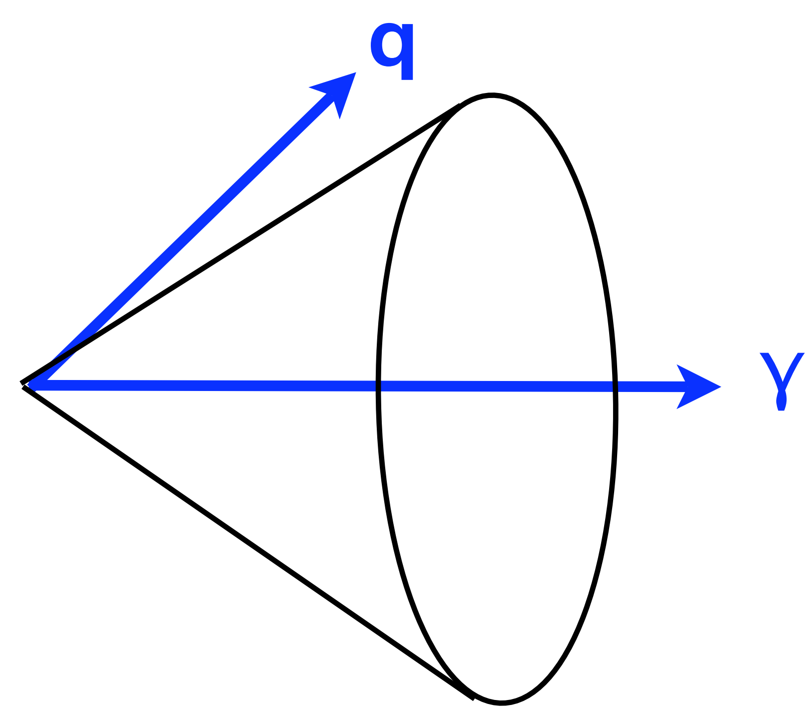
Photons in perturbative QCD

- In the presence of QCD radiation (i.e. beyond LO) cross sections with photons develop additional singularities.



singular propagator when quark and photon are collinear

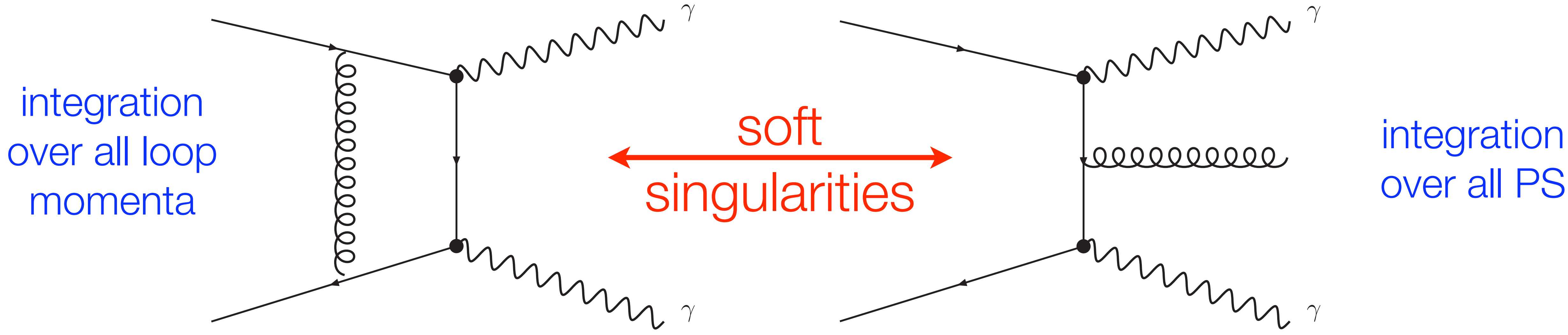
- Naive solution: remove collinear configurations with a cut.



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.
  - must 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.

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

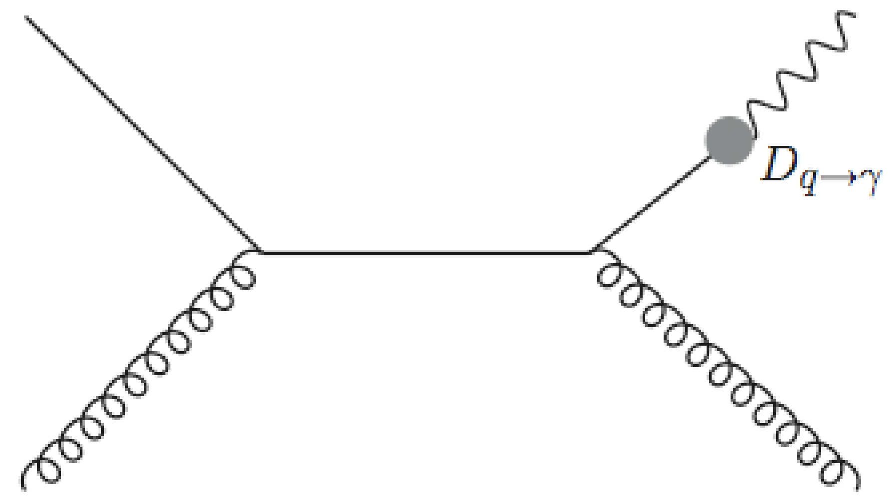
- Okay for QCD infrared-safety, but collinear quark-photon singularity again exposed.
- Singularities can be handled by usual higher-order machinery, e.g. dipole subtraction, and exposed:

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

- 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.

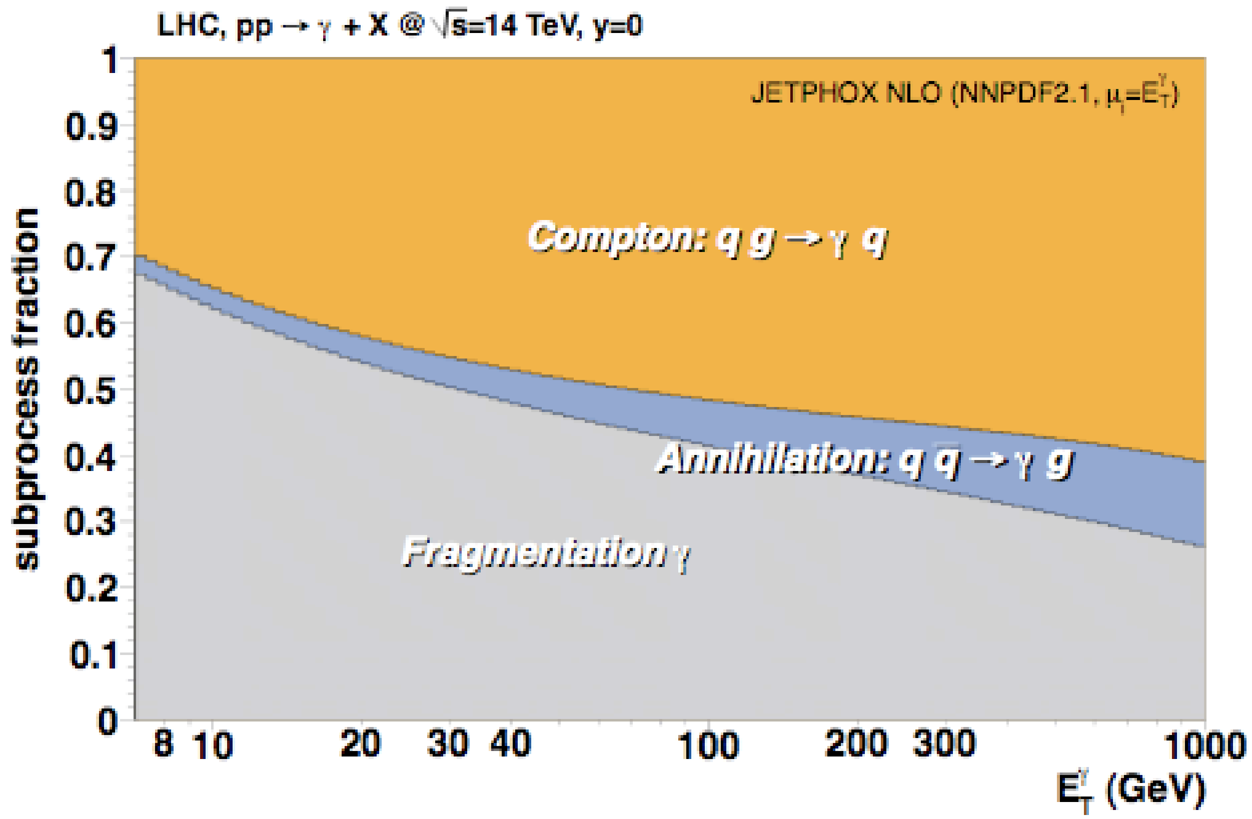


- Using conventional isolation, cross-section now has two components:

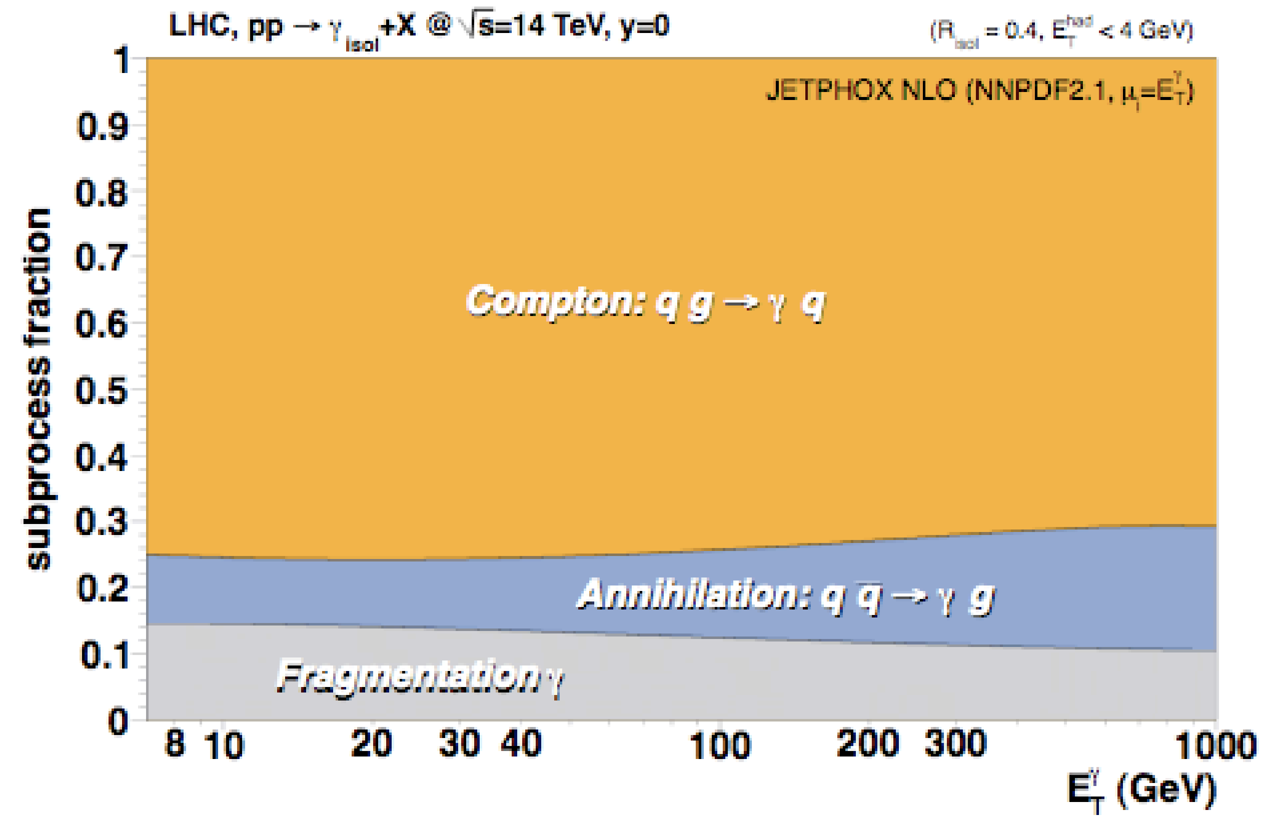
$$\underbrace{\mathrm{d}\sigma = \mathrm{d}\sigma_{\gamma+X}(M_F)}_{\text{direct/prompt}} + \underbrace{\sum_i \mathrm{d}\sigma_{i+X} \otimes D_{i\to\gamma}(M_F)}_{\text{fragmentation}}$$

  - 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

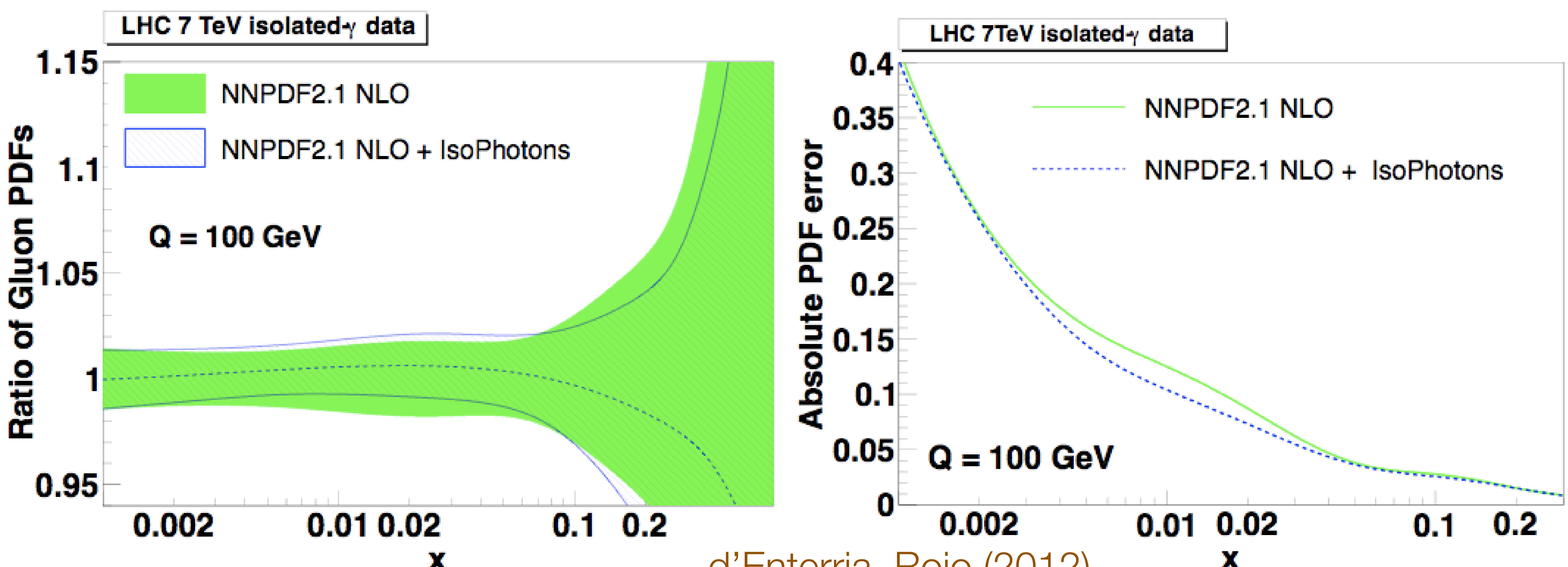


isolated photon

- 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

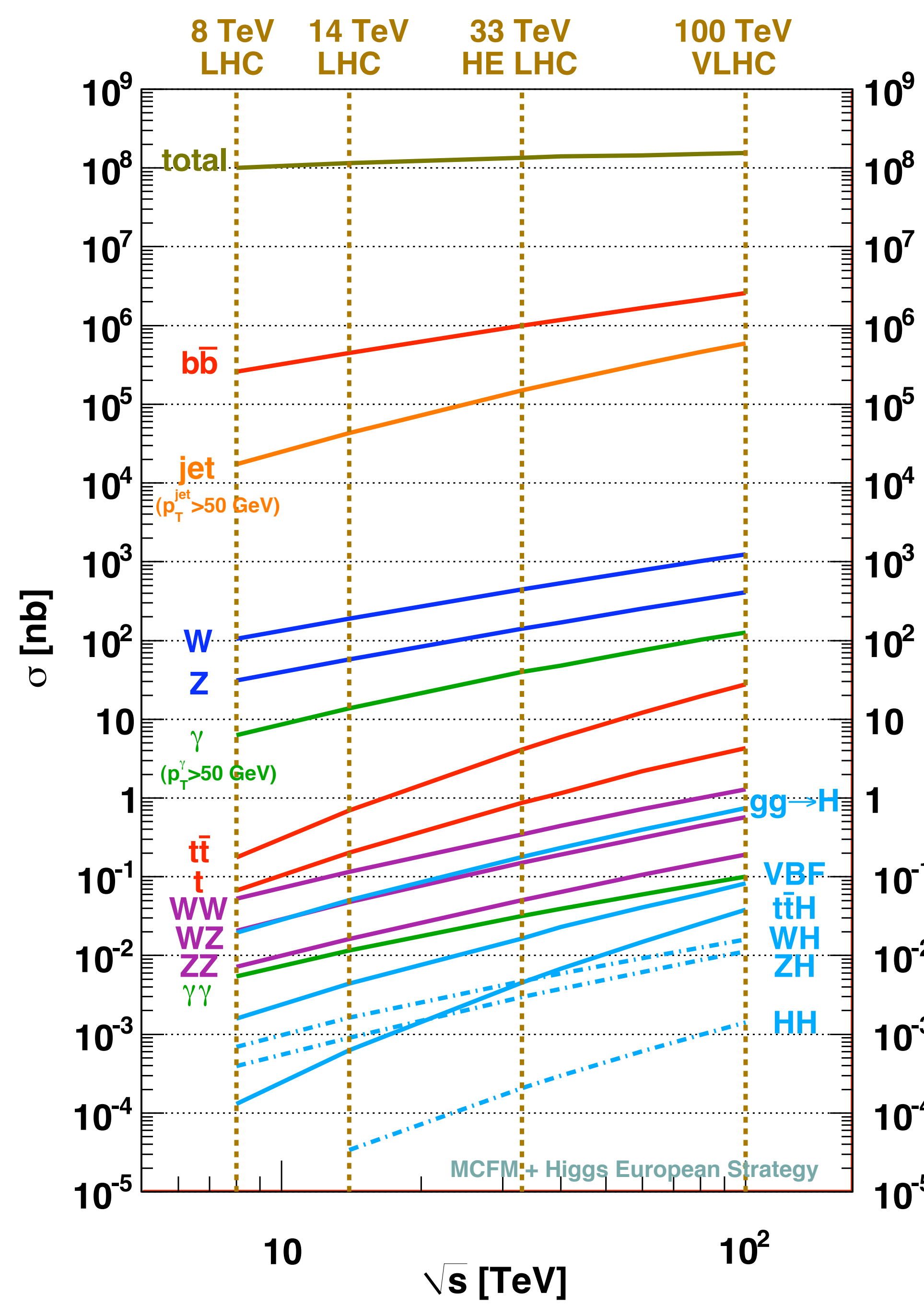
- Study using NNPDF with up to 7 TeV LHC data only
    - shows slight improvement in gluon uncertainty
    - potential for improvement with more data, subject to some limitations: only NLO (NNLO becoming the standard), non-perturbative corrections need to be better-understood.



d'Enterria, Rojo (2012)

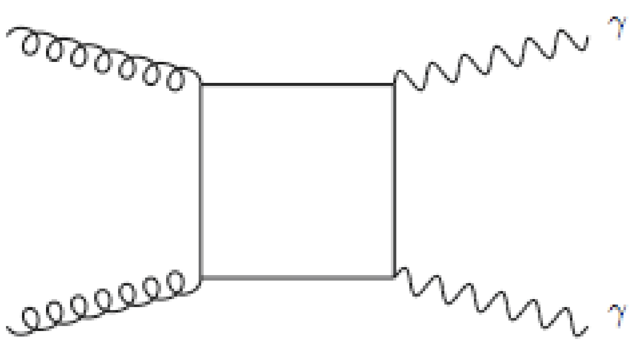
Diphoton production

- Clear interest as the principal background to the Higgs process, gg→H→γγ.
    - even though the background is subtracted with a fitting procedure, it would be nice to 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 basic process: $q\bar{q} \to \gamma\gamma$



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:



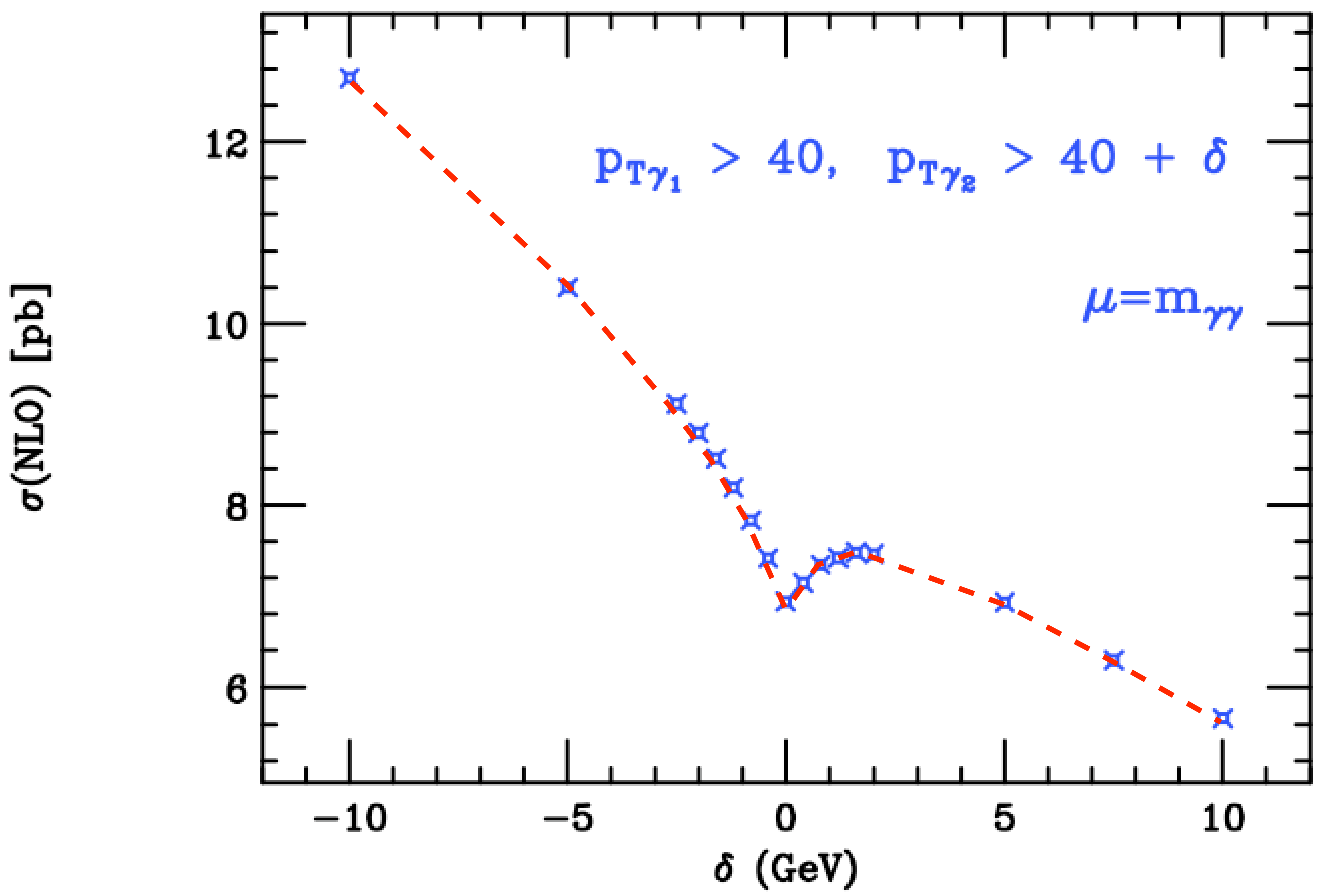
Since there is no tree level ggγγ coupling, this loop contribution is finite
→ can add separately.

(in fact, finite nature means that one can compute corrections to it, i.e. part of N^{3}LO, 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: $p_T^{\gamma_1} > 40 \text{ GeV}\,, \qquad p_T^{\gamma_2} > 40 + \delta \text{ GeV}$
- Causes a problem because in the perturbative calculation 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.

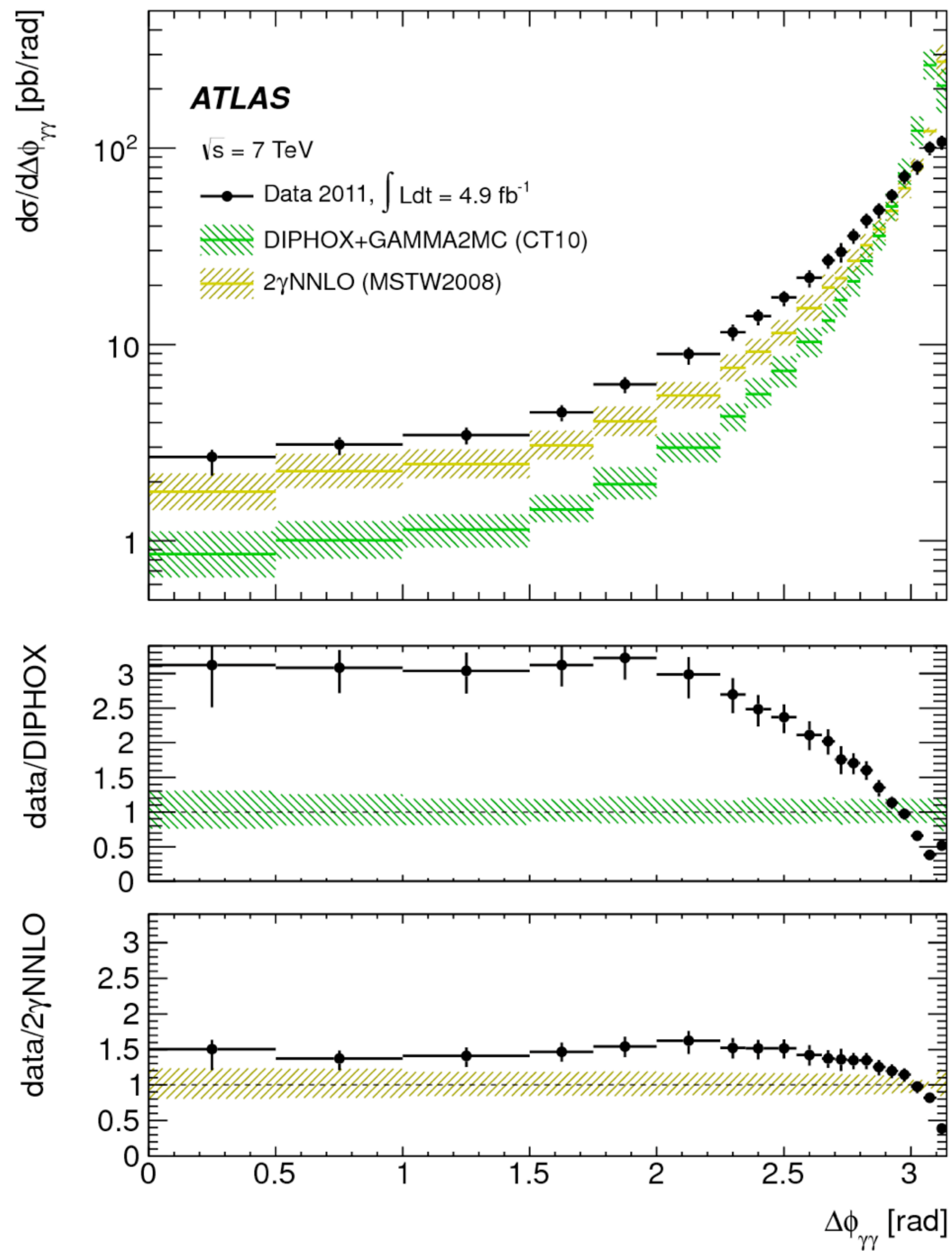
Cusp at δ=0 due to emission of soft gluons and presence of δ log δ enhancement (candidate for resummation).

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.

Vector bosons and direct photons

Lecture 2

CTEQ school 2013

John Campbell, Fermilab

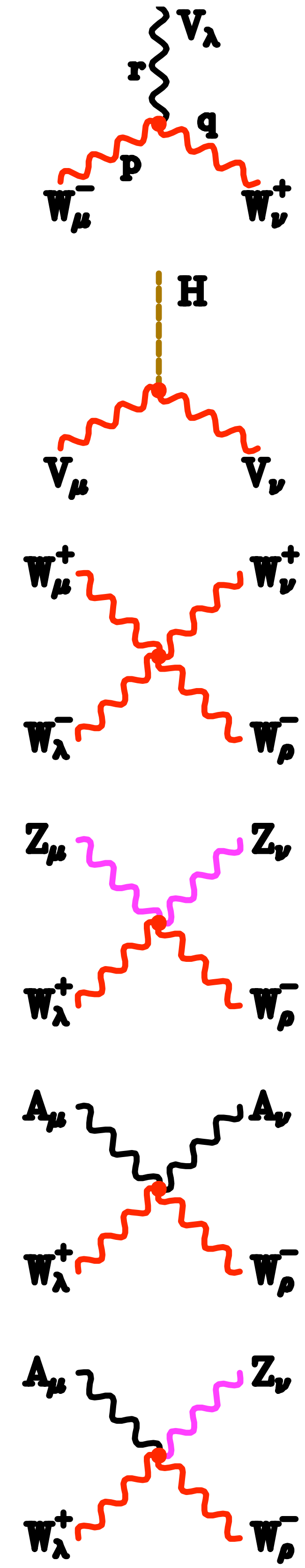
Outline of lectures

- 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.

Weak boson self-interactions

- Now turn to multiple production of vector bosons, with at least one W or Z.
- These have an essentially different character from diphoton production because of self-interactions.
- Probes of triple couplings:
    - Higgs production by VBF
    - decays into W and Z pairs
    - di-boson production
- Probes of quartic couplings:
    - tri-boson production (and beyond)
    - di-boson production through VBF
- Rich structure predicted by the SM Lagrangian to explicitly test.



$$+ig_V\,[(p-q)_\lambda g_{\mu\nu}+(q-r)_\mu g_{\nu\lambda}+(r-p)_\nu g_{\lambda\mu}]$$

(all momenta incoming, $g_A=e$, $g_Z=g_W\cos\theta_W$)

$$+ig_{VH}M_V g_{\mu\nu}$$

($g_{WH}=g_W$, $g_{ZH}=g_W/\cos^2\theta_W$)

$$+ig_W^2[2g_{\mu\nu}g_{\lambda\rho}-g_{\mu\lambda}g_{\nu\rho}-g_{\mu\rho}g_{\nu\lambda}]$$

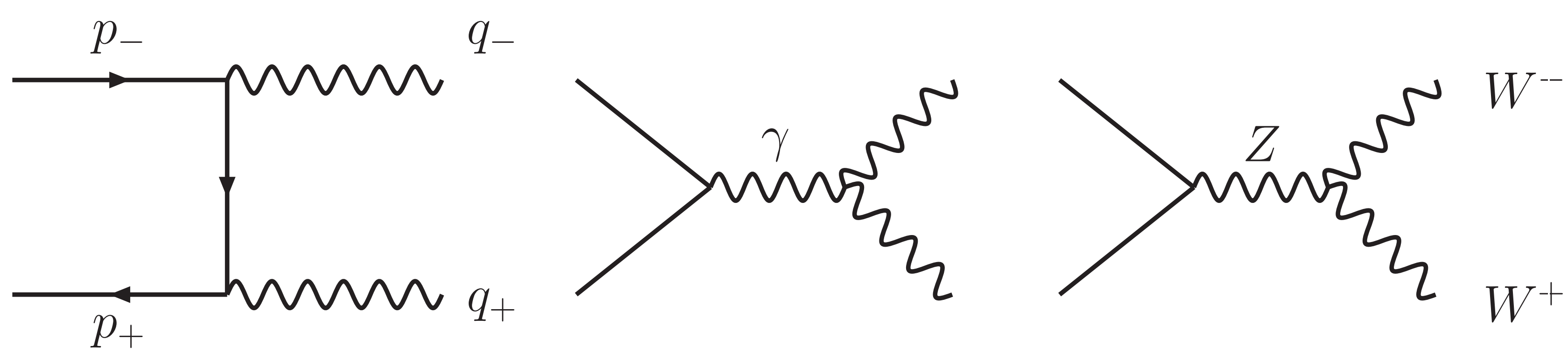
$$-ig_W^2\cos^2\theta_W[2g_{\mu\nu}g_{\lambda\rho}-g_{\mu\lambda}g_{\nu\rho}-g_{\mu\rho}g_{\nu\lambda}]$$

$$-ie^2[2g_{\mu\nu}g_{\lambda\rho}-g_{\mu\lambda}g_{\nu\rho}-g_{\mu\rho}g_{\nu\lambda}]$$

$$-ieg_W\cos\theta_W[2g_{\mu\nu}g_{\lambda\rho}-g_{\mu\lambda}g_{\nu\rho}-g_{\mu\rho}g_{\nu\lambda}]$$

The special role of self-interactions

- To illuminate the special role self-interactions play, consider the reaction $e^+e^-\to W^+W^-$ at a lepton collider.



- Choose frame in which the W 3-momenta are in the *z*-direction:

$$q_\pm = (E, 0, 0, \pm q)$$
$$E^2 - q^2 = m_W^2$$

- Polarization vectors of W ($\epsilon.q = 0$, $\epsilon^2=-1$):

$$\epsilon^\mu = (0,1,0,0), \quad \epsilon^\mu = (0,0,1,0)$$

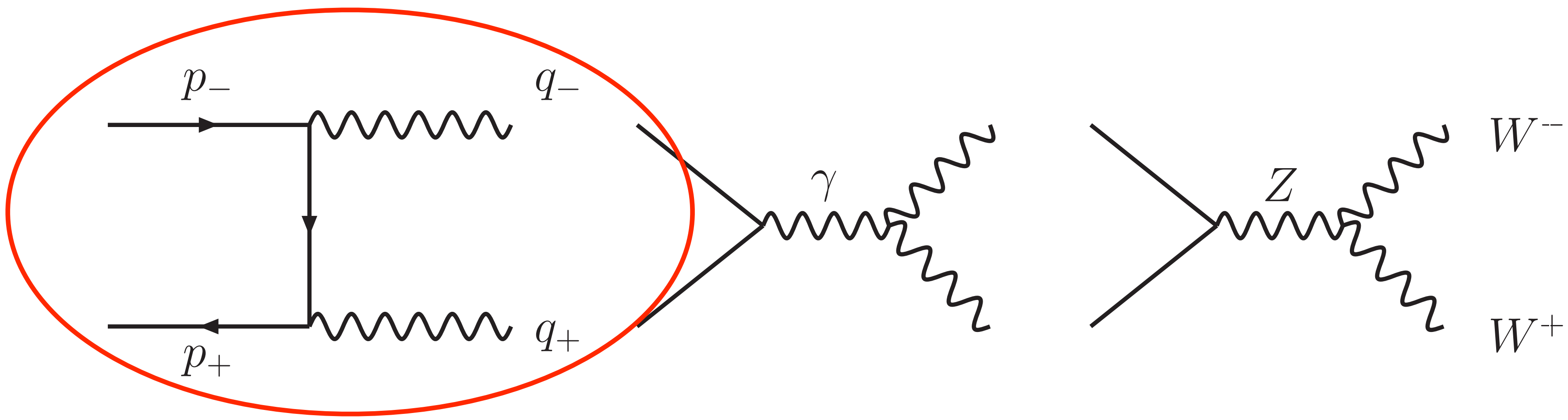
transverse (c.f. photon)

$$\epsilon^\mu_\pm = \frac{1}{m_W}(q, 0, 0, \pm E)$$

longitudinal (massive bosons)

- Longitudinal mode means diagrams grow as E^2 → focus on this limit.
  - in that case can study longitudinal modes by approximating $\epsilon^\mu_\pm \to \dfrac{1}{m_W} q_\pm$

Longitudinal contribution



- Contribution from first diagram:

$$M = \frac{(-ig_w)^2}{8}\bar{v}(-p_+)\not{\epsilon}(q_+)(1-\gamma_5)\frac{i}{\not{p}_- - \not{q}_-}\not{\epsilon}(q_-)(1-\gamma_5)u(p_-)$$

- Using longitudinal polarization and keeping only leading term:

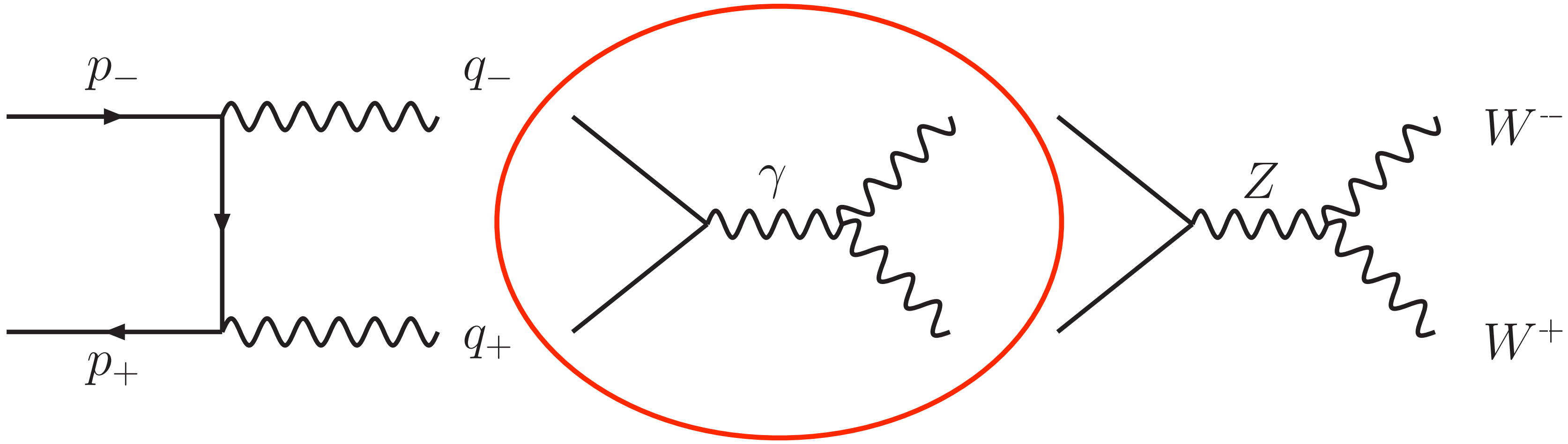
$$M = -i\frac{(-ig_w)^2}{4M_W^2}\bar{v}(-p_+)\not{q}_+(1-\gamma_5)u(p_-)$$

(via equation of motion)

- Useful to rewrite using momentum conservation:

$$M = -i\frac{(-ig_w)^2}{8M_W^2}\bar{v}(-p_+)(\not{q}_+ - \not{q}_-)(1-\gamma_5)u(p_-)$$

Self-coupling contributions



- Contribution from second diagram:

write in terms of g_W using $e=g_W \sin\theta_W$

$$M = (-ig_w)(ig_w)Q_e \sin^2\theta_W \bar{v}(-p_+)\gamma^\rho u(p_-)\frac{-ig_{\rho\alpha}}{(q_+ + q_-)^2} \times V^{\alpha\beta\delta}(q_+ + q_-, -q_-, -q_+)\varepsilon_\beta(q_-)\varepsilon_\delta(q_+)\,.$$

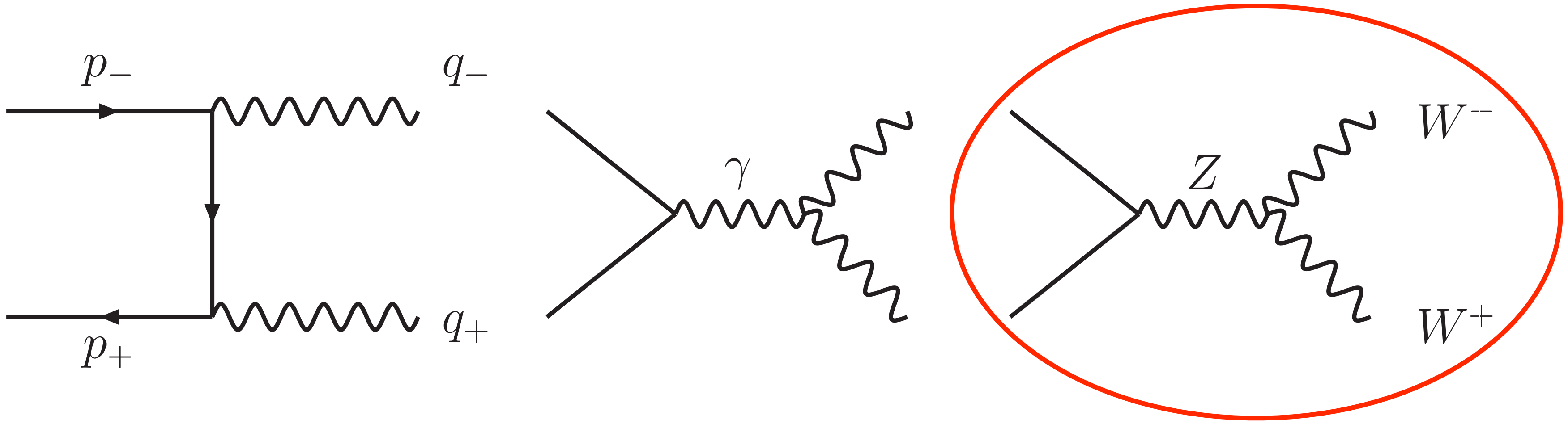
triple-boson vertex

- Triple-boson vertex: $V^{\alpha\beta\delta}(p,q,r) = g^{\alpha\beta}(p^\delta - q^\delta) + g^{\beta\delta}(q^\alpha - r^\alpha) + g^{\delta\alpha}(r^\beta - p^\beta)$
- Contracted with longitudinal polarizations here:

(discard m_W^2)

$$V^{\alpha\beta\delta}(q_+ + q_-, -q_-, -q_+)\varepsilon_\beta(q_-)\varepsilon_\delta(q_+) = -\frac{(q_+ + q_-)^2}{2M_W^2}\left[q_+^\alpha - q_-^\alpha\right] + O(1)$$

Self-coupling contributions



- Similar contribution from third diagram:

vector and axial
couplings from before

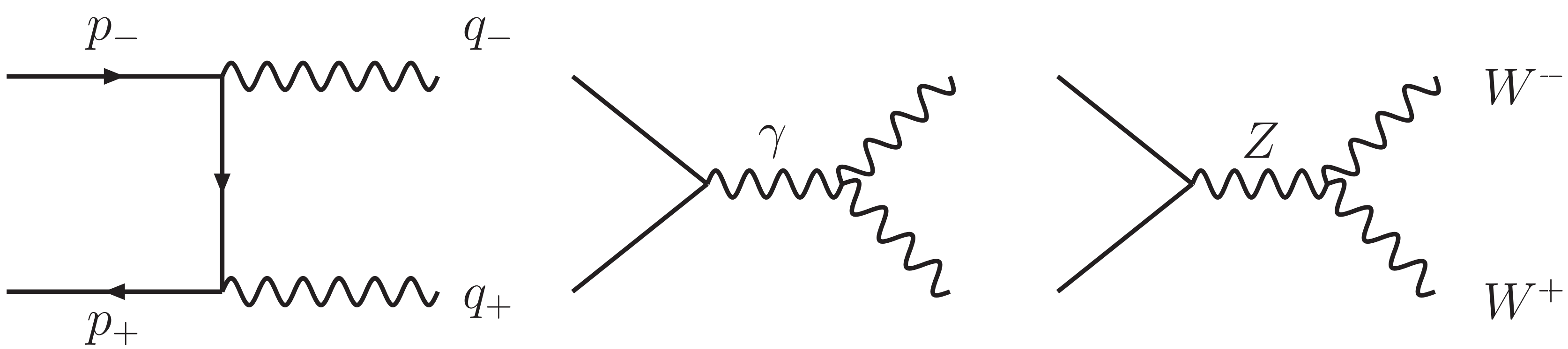
$$
\begin{aligned}
M &= \frac{(-ig_w)(ig_w)}{2}\bar{v}(-p_+)\gamma^\rho(V_e - A_e\gamma_5)u(p_-)\frac{-ig_{\rho\alpha}}{(q_+ + q_-)^2 - M_Z^2} \\
&\times \quad V^{\alpha\beta\delta}(q_+ + q_-, -q_-, -q_+)\varepsilon_\beta(q_-)\varepsilon_\delta(q_+)
\end{aligned}
$$

- Hence, combining second and third diagrams:

$$
M = -i\frac{(-ig_w)^2}{4M_W^2}\bar{v}(-p_+)(\not{q}_+ - \not{q}_-)\left[2Q_e\sin^2\theta_W + V_e - A_e\gamma_5\right]u(p_-)
$$

(discarding non-leading terms)

Total in the high-energy limit



$$M = -i\frac{(-ig_w)^2}{8M_W^2}\bar{v}(-p_+)(\not{q}_+ - \not{q}_-)\left[1 + 4Q_e\sin^2\theta_W + 2V_e - (1+2A_e)\gamma_5\right]u(p_-)$$

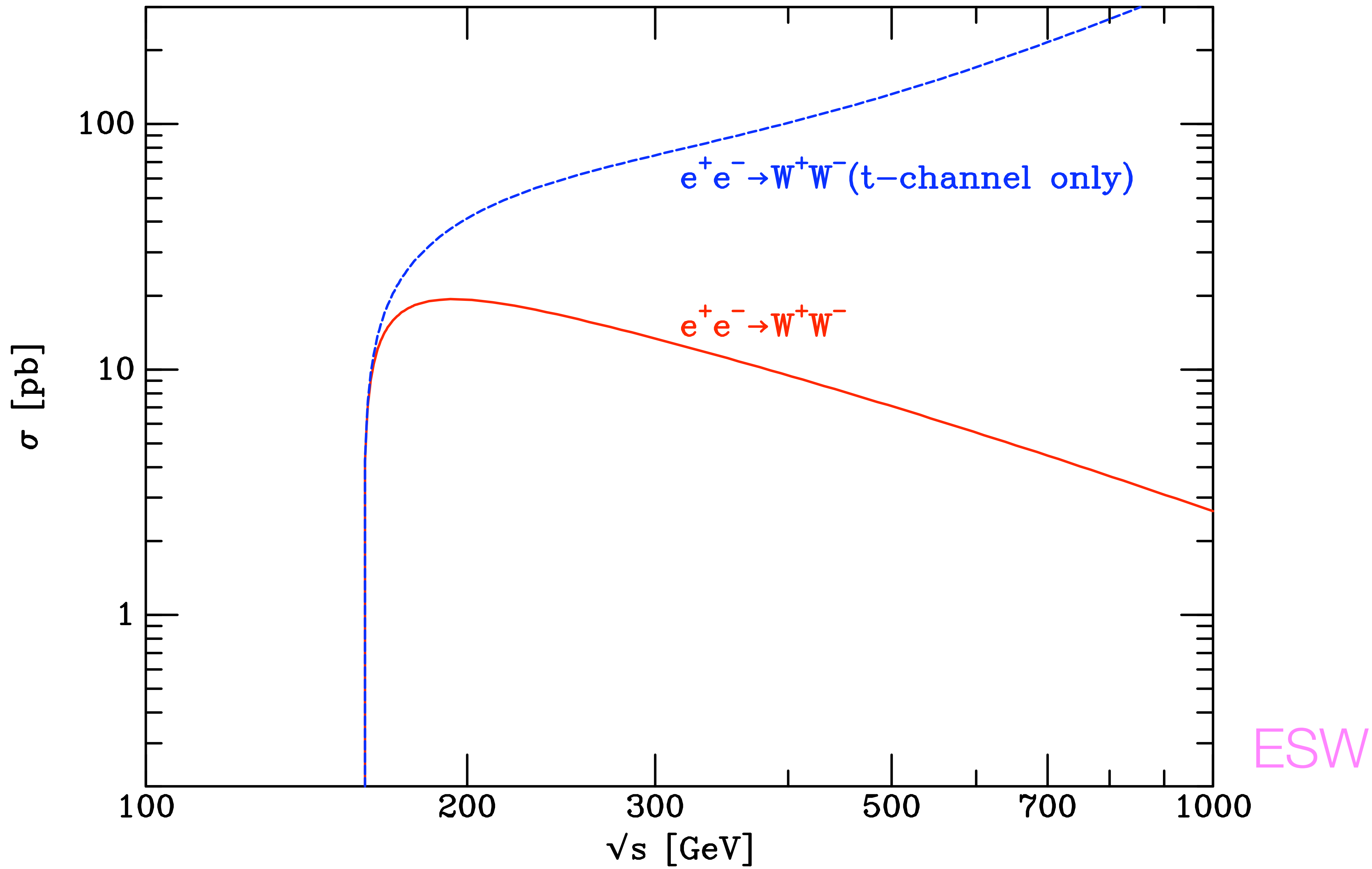
- Recall definitions of Z couplings: $V_e = -\frac{1}{2} - 2Q_e\sin^2\theta_W\,, \qquad A_e = -\frac{1}{2}$

  to see that the leading high-energy behaviour is cancelled.

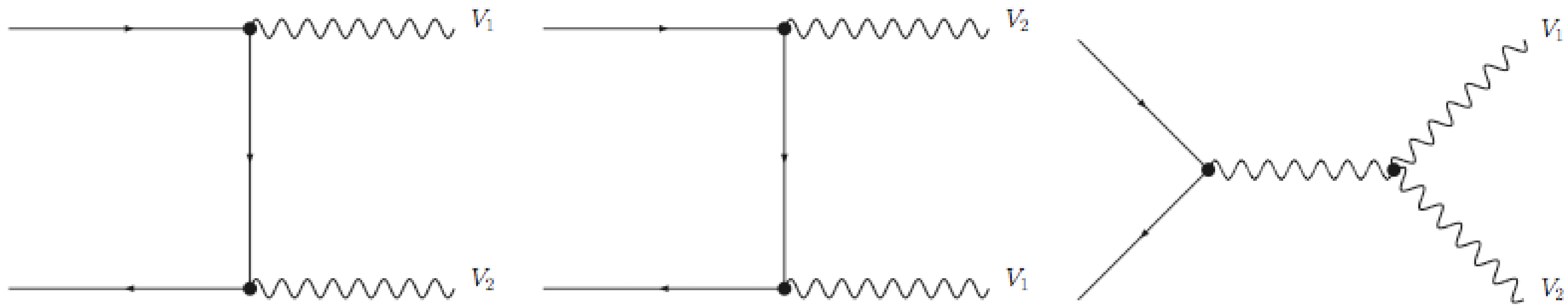
  - due to the relationship between the coupling of the W,Z and photon to fermions and the triple-boson couplings
  - equivalently, due to the underlying gauge structure of the weak sector of the Standard Model.
  - imperative to test at hadron colliders.

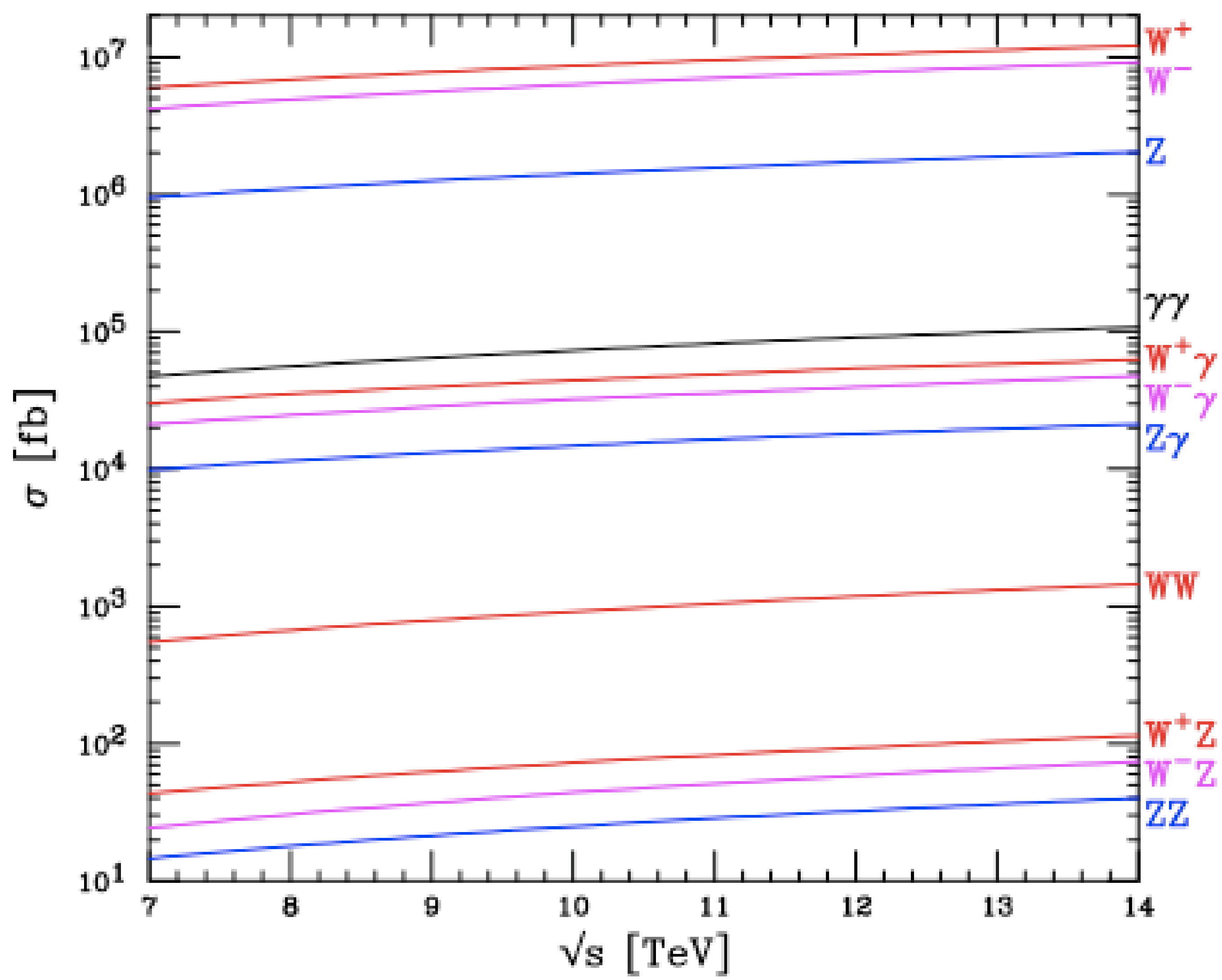
Strength of high-energy cancellation

- Full result including sub-leading terms.



Diboson production at hadron colliders

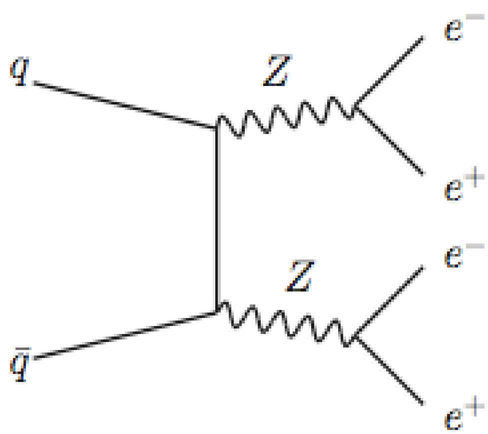




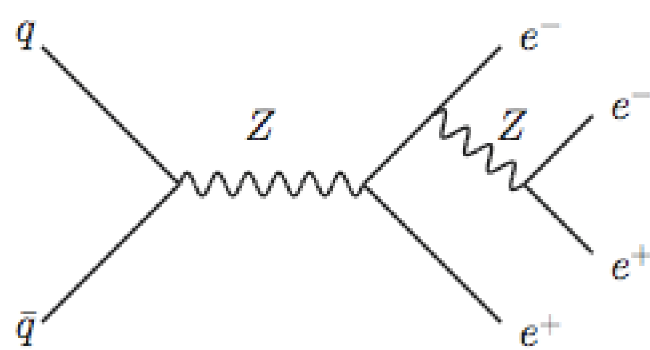
- Tri-boson coupling present for all processes except Zγ.
- Processes involving photons strongly-dependent on photon p_T (and rapidity) cut.
- Further suppression by BRs once decays are included.
- Next-to-leading order corrections known analytically, included in MCFM, VBFNLO.

Single-resonant diagrams

- Modern calculations of the diboson processes include effects of decays; in that case, EW gauge invariance requires that additional diagrams are included.



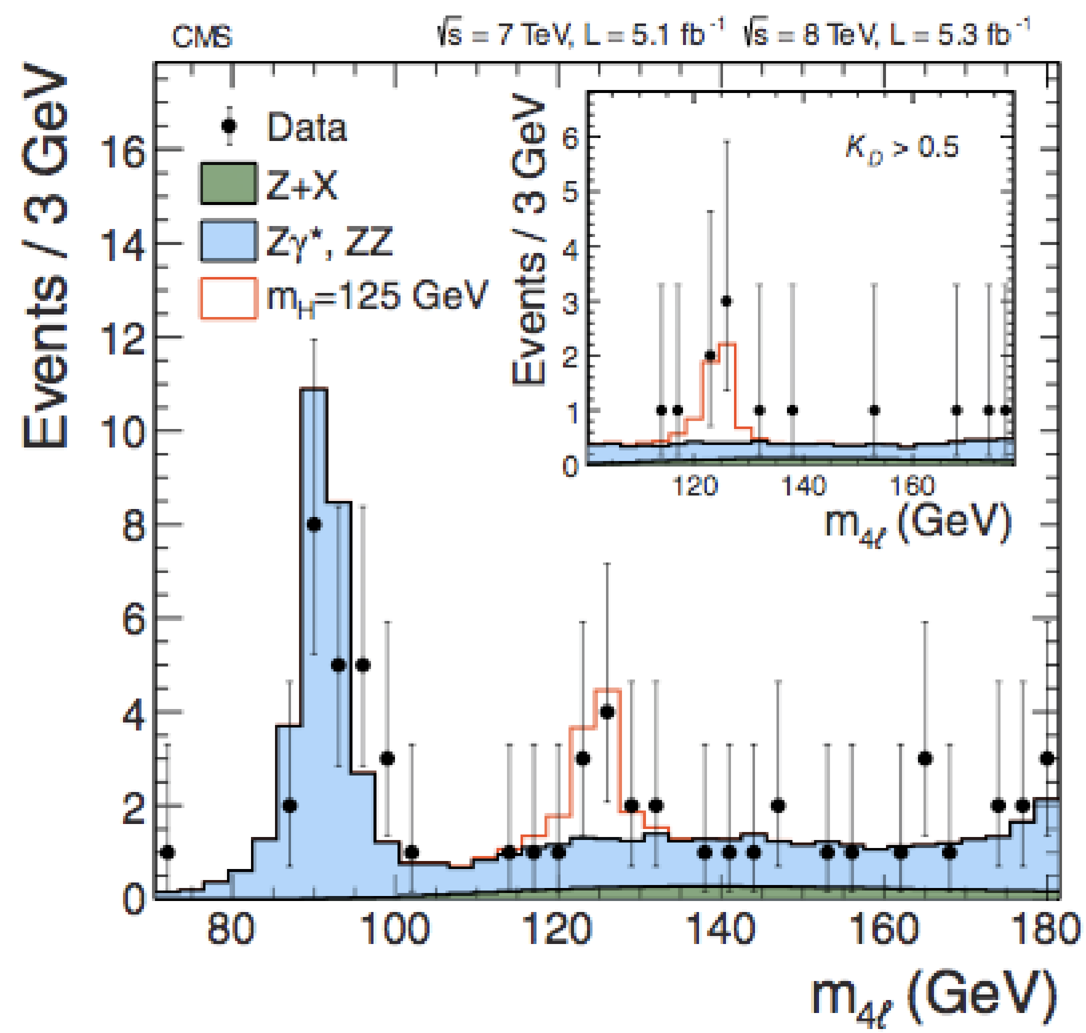
“double”-



“single”-resonant

$qq \rightarrow ZZ \rightarrow e^+e^-e^+e^-$

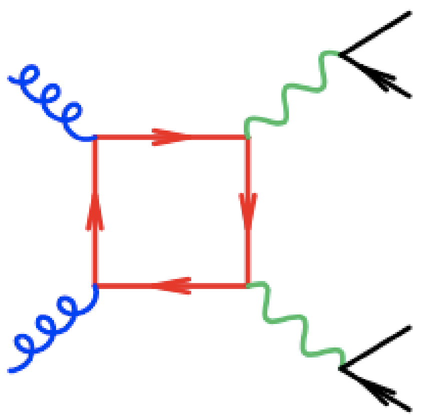
CMS-HIG-12-028

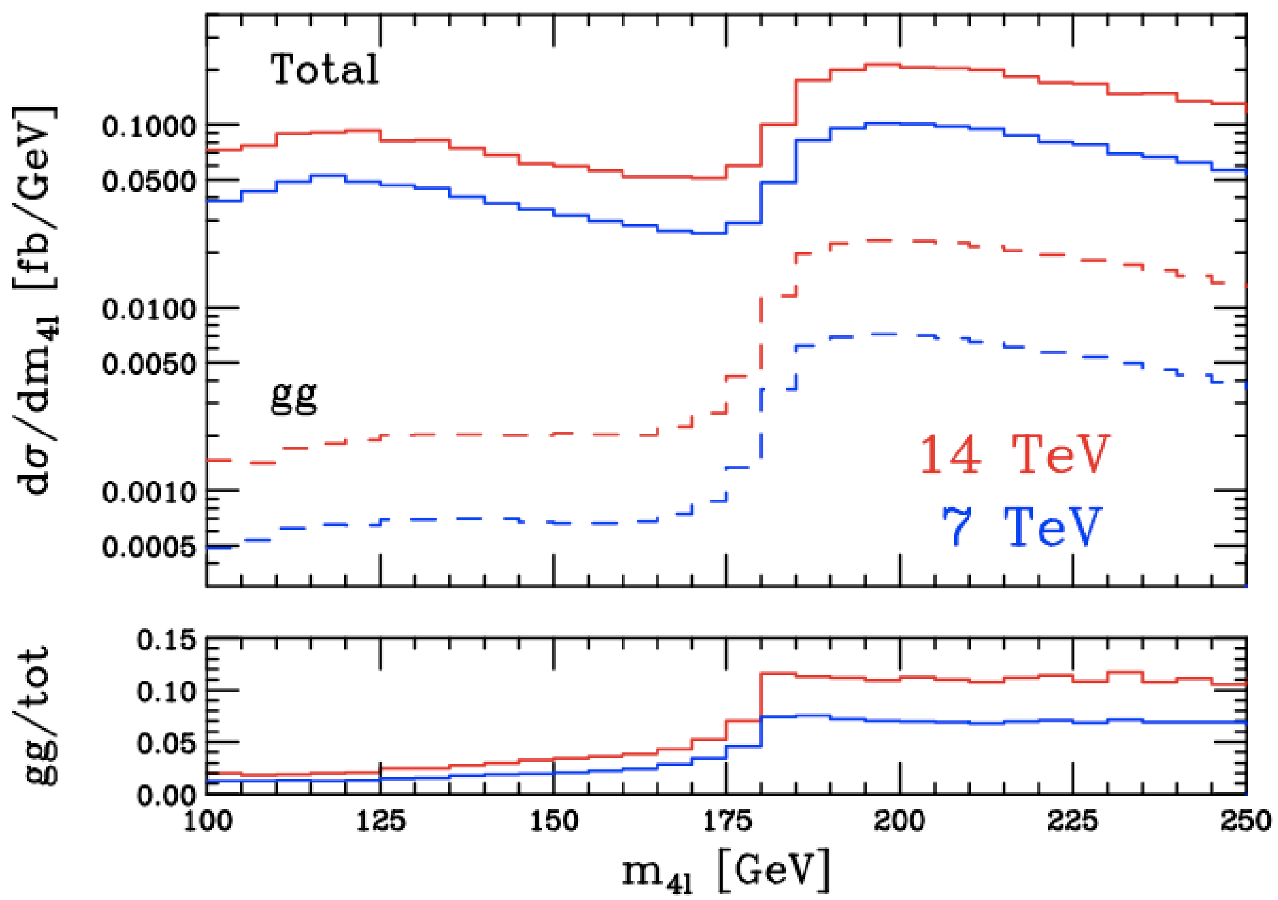


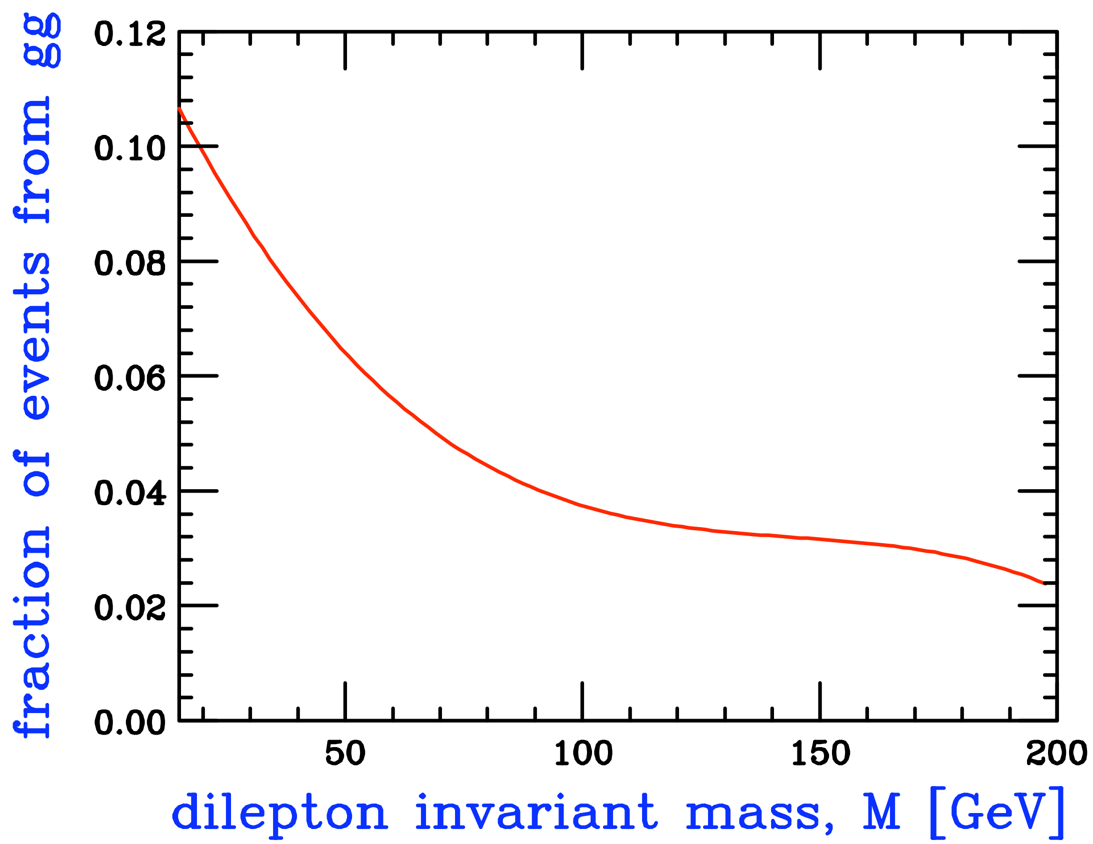
- Inclusive cross section is dominated by the double-resonant contribution, but other distributions can be sculpted.
- Notably: invariant mass of 4 leptons.
- Useful cross-check of analysis in Higgs search.

Gluon-induced contributions

- Just like diphoton production, part of NNLO contribution to WW and ZZ production is numerically relevant at the LHC.





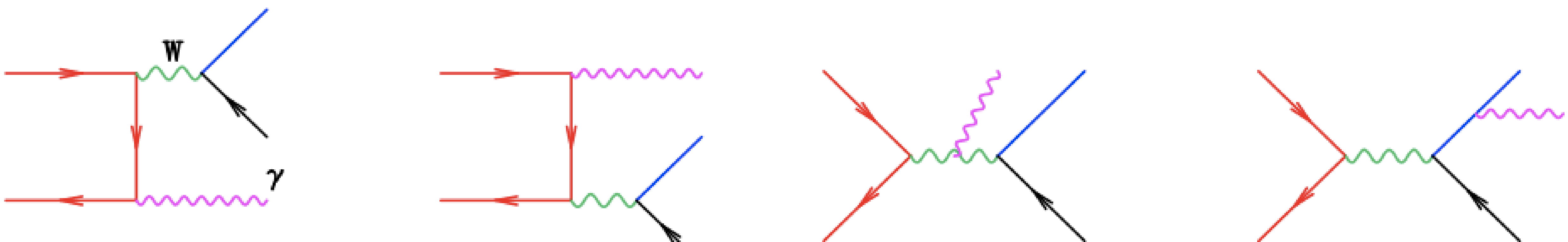


ZZ: small below Z pair threshold (e.g. H search), but large above

WW: impact of gg contribution enhanced by H analysis cuts such as low dilepton invariant mass

Photon radiation in decays

- For Wγ and Zγ production it is essential to account for the effect of photon radiation from the products of the W or Z decay.



(a) (b) (c) (d)

  - required by EM gauge invariance unless dileptons confined to resonance region → not always easy to enforce experimentally
  - effect can be dramatic $\sigma(e^+\nu\gamma) \neq \sigma(W^+\gamma) \times \mathrm{Br}(W^+ \to e^+\nu)$

W on-shell (no FSR)

W off-shell (includes FSR)

Decay	Cuts	$\sigma^{LO}(e^+\nu\gamma)$	$\sigma^{NLO}(e^+\nu\gamma)$
No FSR	Basic γ	4.88	8.74
	M_T cut	1.99	3.78
	Lepton cuts	1.49	2.73
Full	Basic γ	23.0	30.1
	M_T cut	2.12	3.94
	Lepton cuts	1.58	2.85

difference reduced by transverse mass cut $M_T(\ell\gamma,\nu)>90$ GeV

→ no room left to radiate in decay

W+photon amplitude

- Consider the lowest order partonic process (4-momenta in brackets):

$$\bar{u}(p_1) + d(p_2) \rightarrow W^+ + \gamma(p_3)$$

- The helicities of the quarks are fixed by the W coupling but we choose a positive helicity photon. Up to an overall factor amplitude is:

$$Q_u \frac{[2\,3]}{\langle 1\,3 \rangle} + Q_d \frac{[1\,3]}{\langle 2\,3 \rangle} \qquad Q_u = 2/3 \text{ and } Q_d = -1/3$$

(and we have used $Q_e = Q_d - Q_u$ to simplify)

- Convert back to more-familiar dot products by extracting overall spinor factor:

$$\frac{[2\,3]}{\langle 1\,3 \rangle} \left(Q_u + Q_d \frac{p_1 \cdot p_3}{p_2 \cdot p_3} \right) \qquad (\text{recall, } \langle i\ j \rangle [j\ i] = 2 p_i \cdot p_j)$$

- Can now evaluate in the partonic c.o.m. Assume the down quark has a positive *z* component and denote the angle between it and the photon by θ*.
- Amplitude thus proportional to: $Q_u(1+\cos\theta^\star) + Q_d(1-\cos\theta^\star)$

Radiation amplitude zero

- Amplitude vanishes at the scattering angle given by:

$$\cos\theta^\star = \frac{Q_u + Q_d}{Q_d - Q_u} = -\frac{1}{3}$$ (independent of parton energies)

- This feature is characteristic of all helicity amplitudes for the emission of photons in multi-boson processes.
- "Radiation amplitude zero" (RAZ) the result of interference between diagrams.
- Easy to calculate the corresponding photon rapidity:

$$y_\gamma^\star = \frac{1}{2}\log\left(\frac{1+\cos\theta^\star}{1-\cos\theta^\star}\right) \approx -0.35$$

- Rather than reconstructing all objects and trying to boost back to c.o.m, easiest to construct a (boost invariant) rapidity difference: $\Delta y^\star = y_\gamma^\star - y_W^\star$.
- For small photon p_T relative to m_W the W rapidity in the c.o.m. is given by:

$$y_W^\star \approx \frac{1}{2}\log\left(\frac{m_W - p_T^\gamma\cos\theta^\star}{m_W + p_T^\gamma\cos\theta^\star}\right)$$

Position of zero

- Expanding for small p_T gives: $y^\star_\gamma \approx \dfrac{p_T^{\gamma,\min}}{3m_W}$

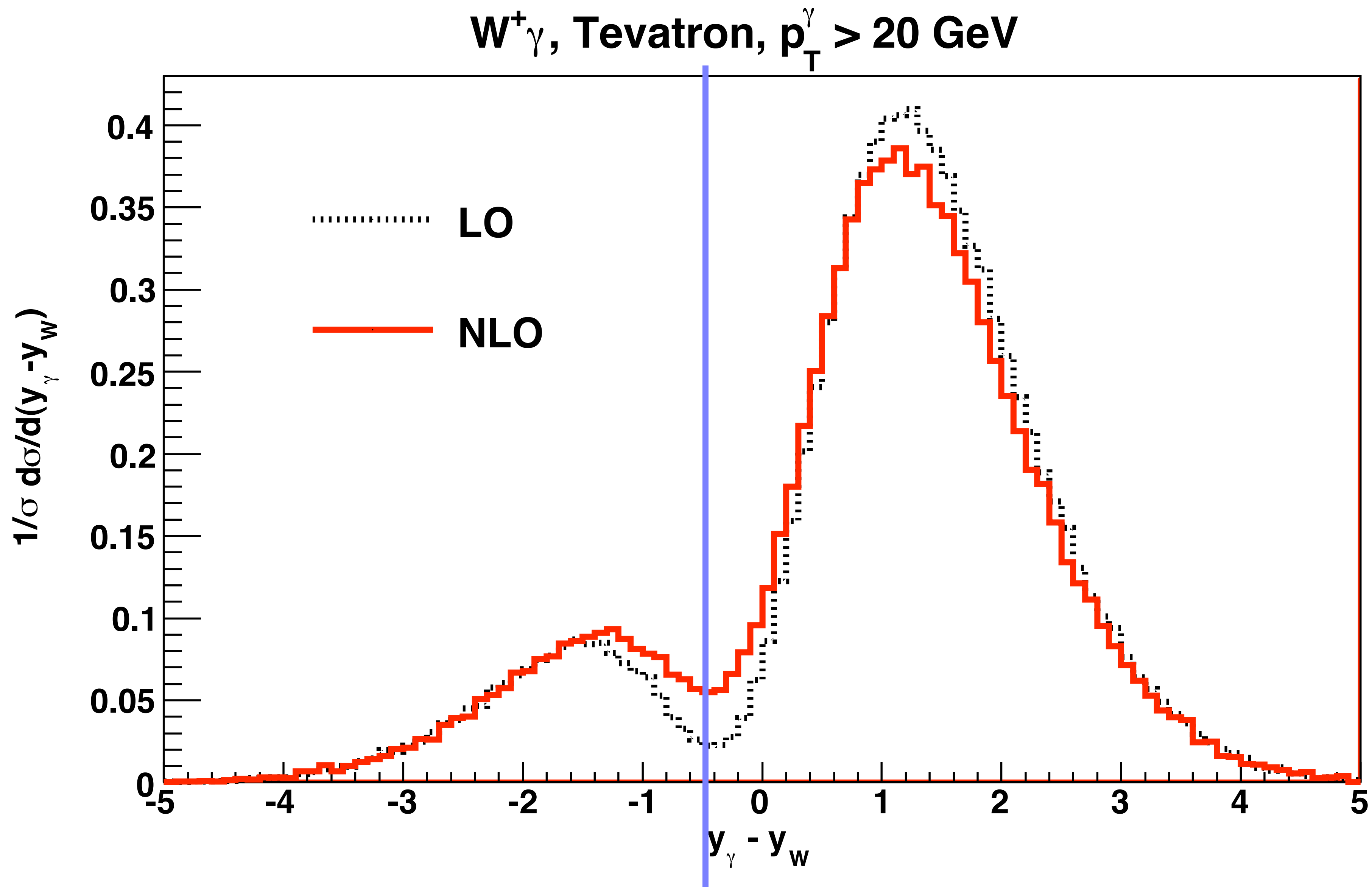
- Hence the corresponding zero in the W rapidity distribution is positive, but at a significantly smaller value.

- Rapidity difference, e.g. for typical experimental cuts at 20 GeV: $\Delta y^\star \approx -0.45$ (for the sub-process we looked at).

- Tevatron: quark and anti-quark directions coincide with those of protons and anti-protons, to first approximation.
  - prediction for the radiation zero derived above should be reproduced approximately once pdfs are folded in;
  - this pdf dilution means that we do not obtain exact vanishing of the distribution but instead a pronounced dip.

- LHC: no well-defined direction for protons, so RAZ should be at $\Delta y^*=0$.

Radiation zero at the Tevatron



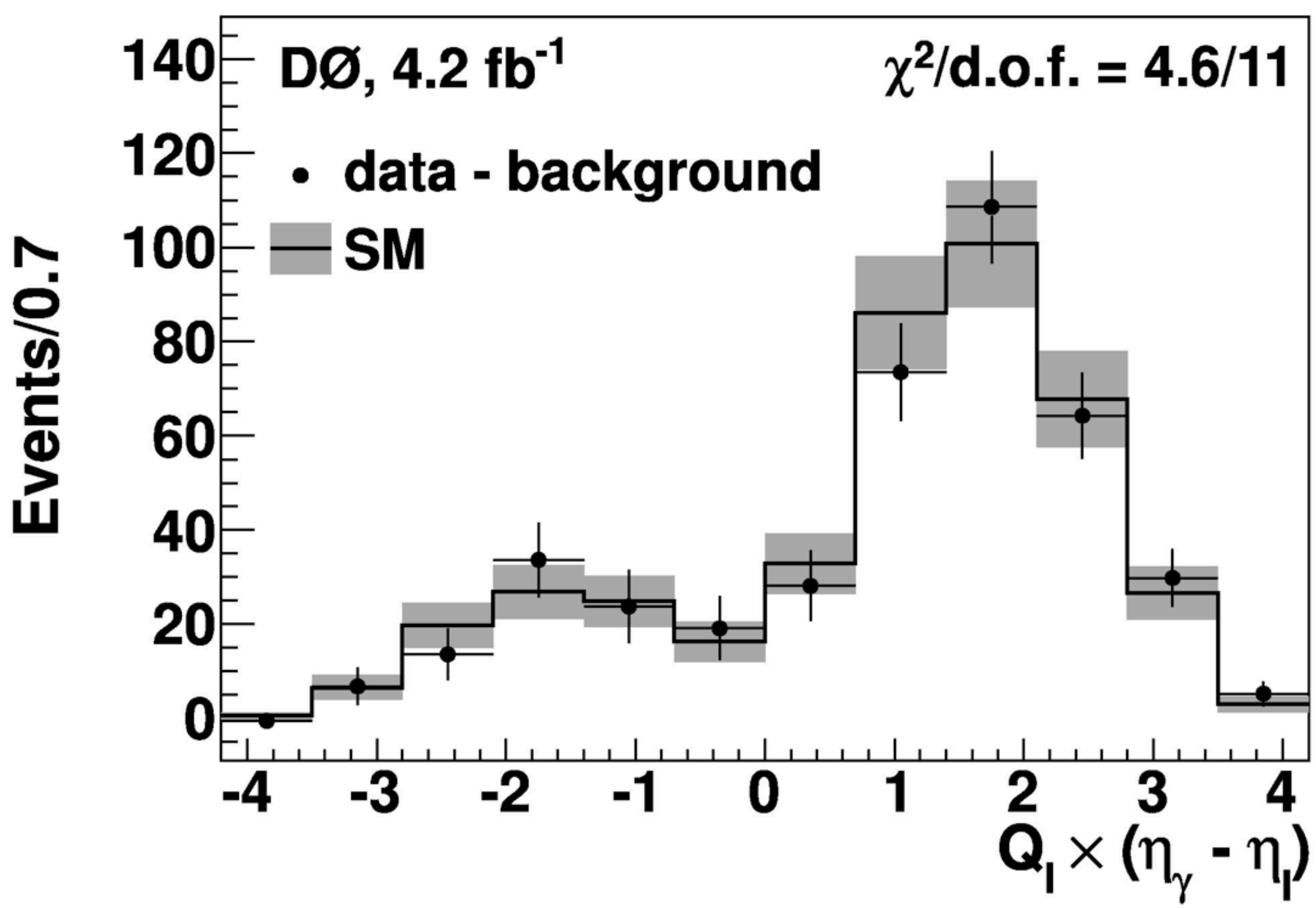
expected position of RAZ

Amplitude zero a feature of the LO amplitude only
→ partially washed out at higher orders

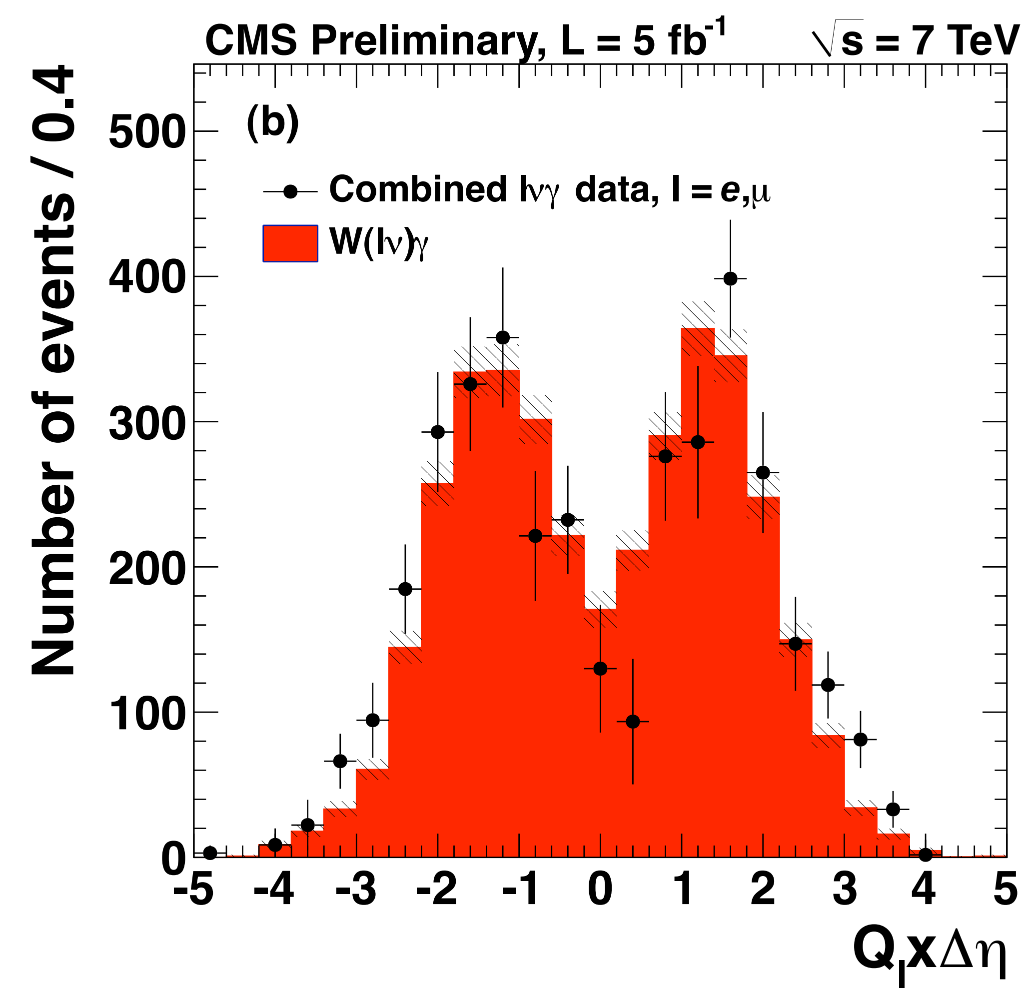
Experimental evidence for RAZ

- Experimental issues that wash out dip:
  - easiest to use lepton rapidity rather than W (retains much information)
  - contamination from photon radiation in W decay

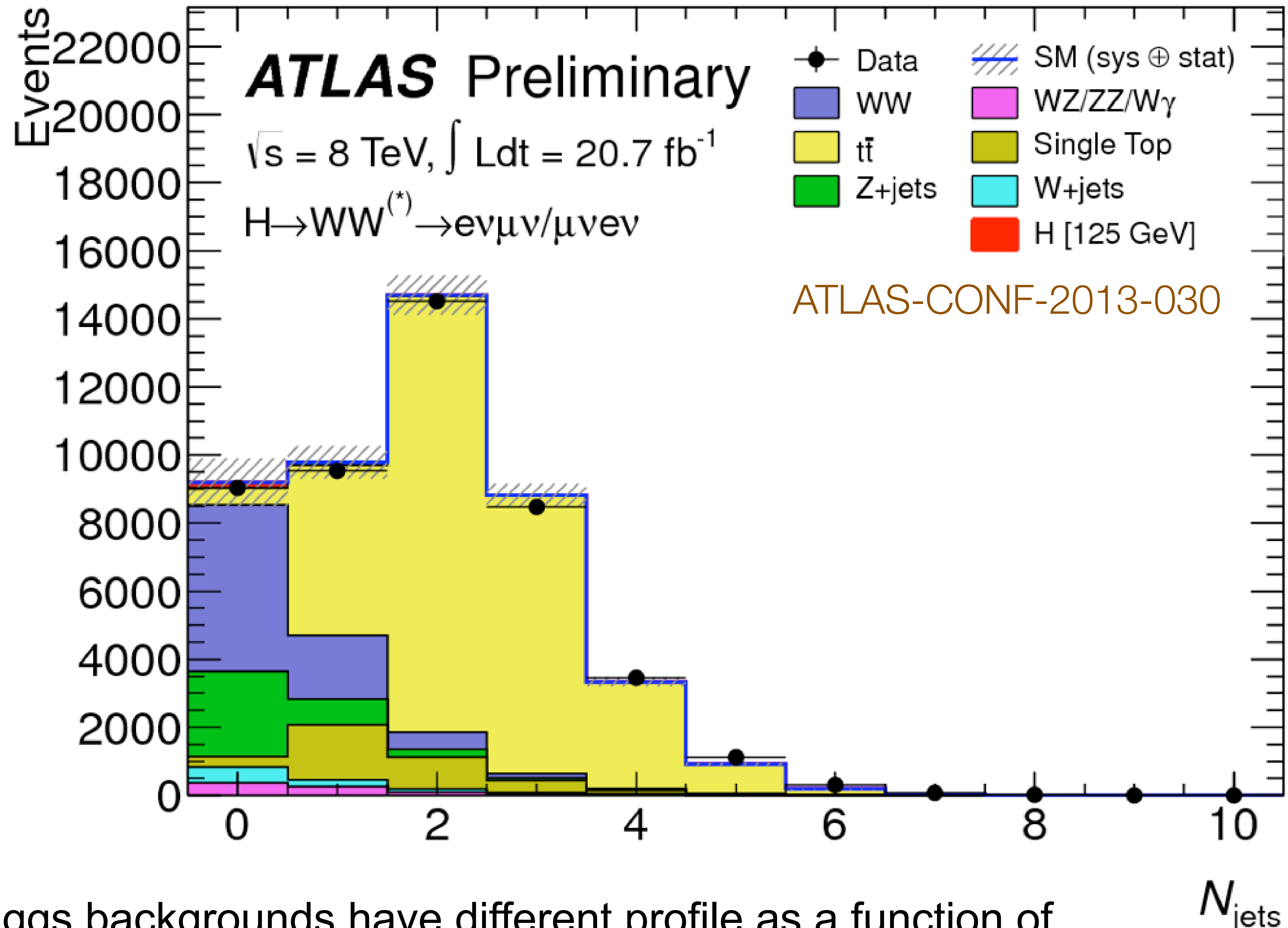
D0, arXiv 1109.4432



CMS, PAS-EWK-11-009



WW: the importance of jet-binning



- Higgs backgrounds have different profile as a function of number of jets → important to understand theory the same way.

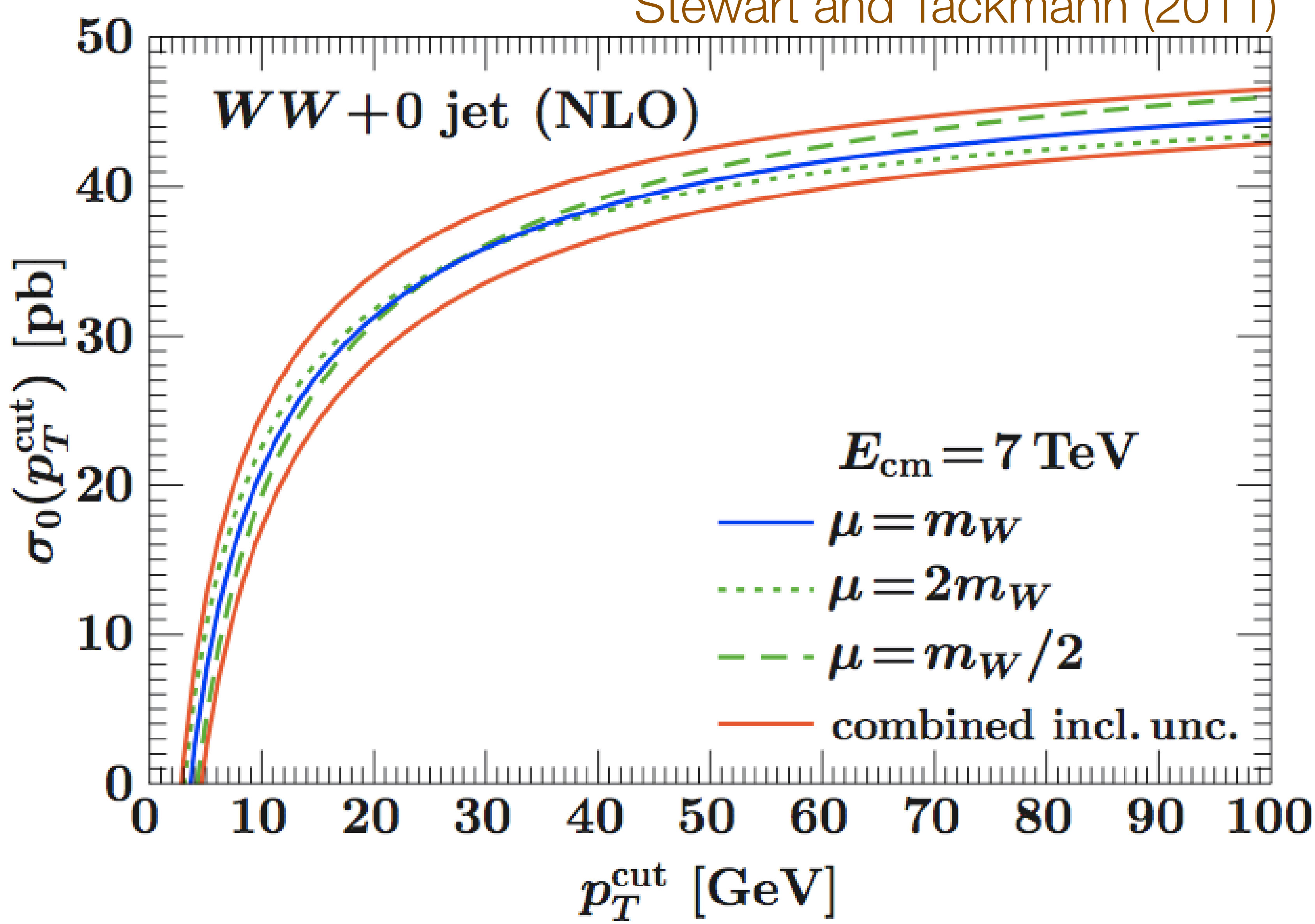
Jet vetoes

- Top backgrounds naturally contain jets: at least partly understood via well-known weak interaction.
- In contrast, WW process only produces jets through QCD.
  - jet-binned cross sections can be subject to large uncertainties.
- The reason is that the veto is explicitly removing part of the real radiation that is responsible for ensuring that infrared divergences cancel
  - the incomplete cancellation that results introduces a logarithm into the perturbative expansion
  - consider an inclusive WW cross section at NLO; vetoing jets to obtain the 0-jet cross-section is removing a term of order $\boldsymbol{\alpha_s}$
  - however, the derivation of the Sudakov factor we sketched earlier tells us that we're actually introducing a factor more like $\alpha_s \log^2[2m_W/p_T^{veto}]$; for typical values of the veto this factor is numerically large ~ 3.
  - we should therefore expect worse perturbative behaviour.

Vetoed uncertainties

- However, the naive method of scale variation can be too optimistic and result in uncertainties for vetoed cross sections smaller than for the inclusive case.
- The accidentally-small variation can be undone by assuming the scale uncertainties in the 0-jet and 1-jet bins are uncorrelated.

Stewart and Tackmann (2011)



$$\Delta^2_{0-\text{jet}} = \Delta^2_{\text{incl.}} + \Delta^2_{1-\text{jet}}$$

New uncertainty much larger across the range of p_T

Some empirical evidence that this may be *too* conservative

Real answer is to resum the logarithms →much work in H case.

Anomalous triple gauge couplings

- aTGCs usually described in terms of additional interactions in the Lagrangian:

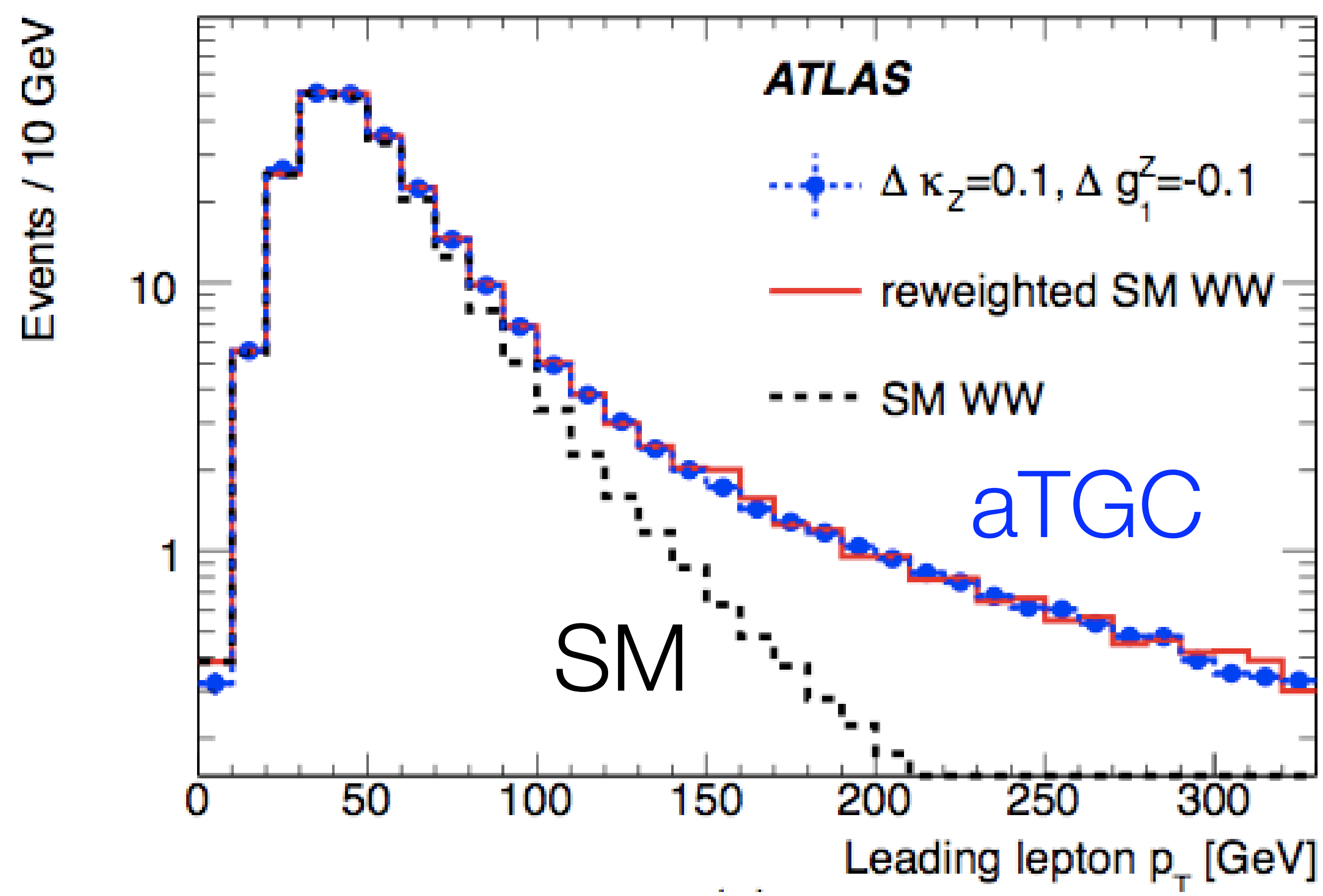
$$\mathcal{L}_{anom} = ig_{WWZ}\left[\Delta g_1^Z\left(W^*_{\mu\nu}W^\mu Z^\nu - W_{\mu\nu}W^{*\mu}Z^\nu\right) + \Delta\kappa^Z W^*_\mu W_\nu Z^{\mu\nu} + \frac{\lambda^Z}{M_W^2}W^*_{\rho\mu}W^\mu_\nu Z^{\nu\rho}\right] + ig_{WW\gamma}\left[\Delta\kappa^\gamma W^*_\mu W_\nu \gamma^{\mu\nu} + \frac{\lambda^\gamma}{M_W^2}W^*_{\rho\mu}W^\mu_\nu\gamma^{\nu\rho}\right]$$

- Most general contribution that separately conserves C and P.

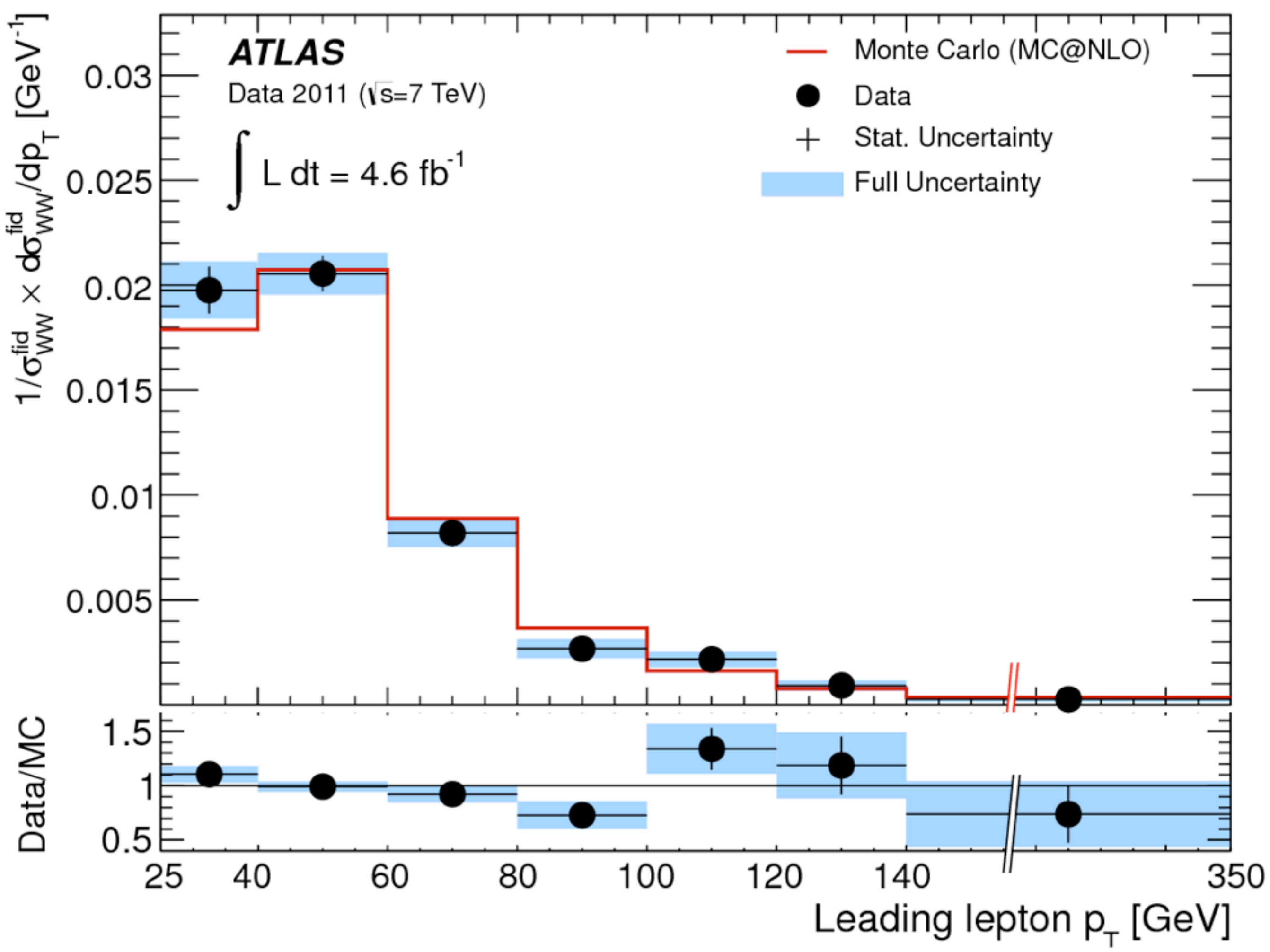
- Operators do not change the predicted cross-section significantly, but instead alter distributions at high p_T, invariant mass, etc.

- This plot, for illustration, uses values of parameters outside current exclusion.
  - need to look for small deviation in tail.

CERN-PH-EP-2012-242

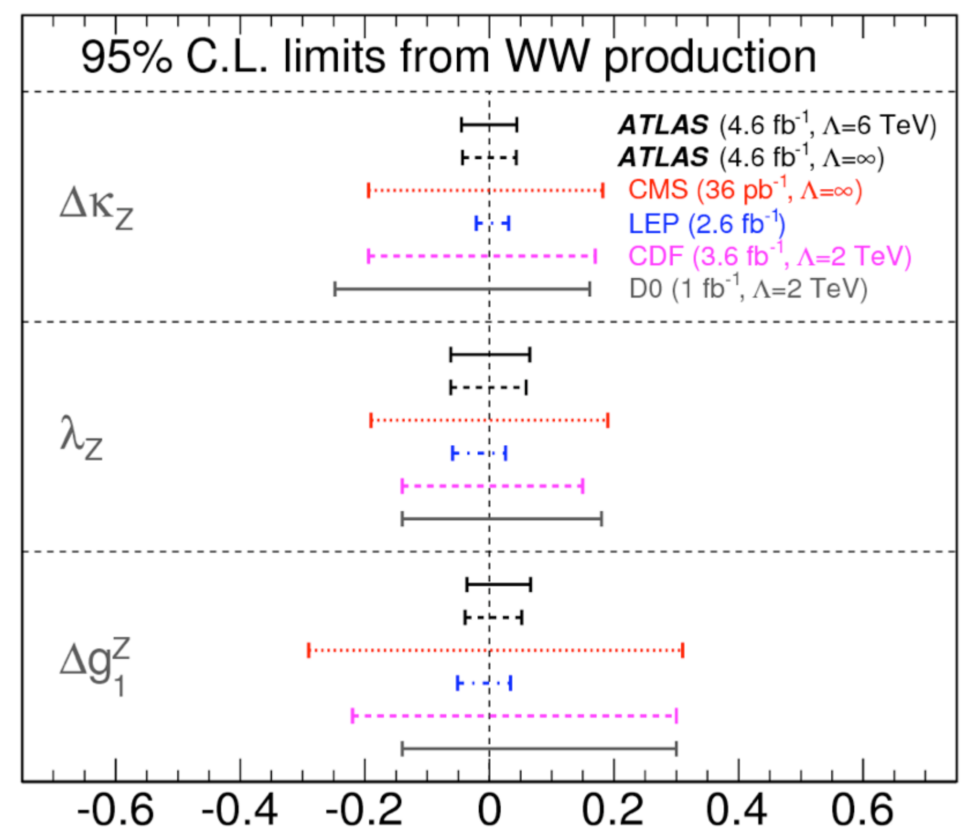


Example of result



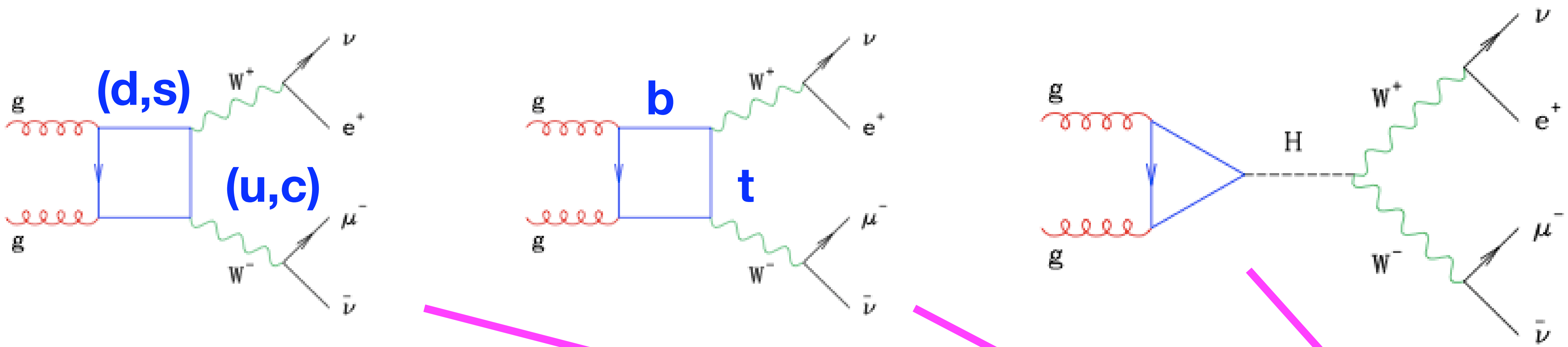
ATLAS WW analysis

Comparison with CMS, Tevatron and LEP



A bit beyond vector bosons ...

- The gluon-initiated WW contribution has the same external particles as the Higgs production process. Should calculate full amplitude before squaring:



$$\mathcal{A}_{\rm full} = \delta^{a_1 a_2}\left(\frac{g_w^4 g_s^2}{16\pi^2}\right)\mathcal{P}_W(s_{34})\mathcal{P}_W(s_{56})\ [2\,\mathcal{A}_{\rm massless}+\mathcal{A}_{\rm massive}+\mathcal{A}_{\rm Higgs}]$$

- Is the interference important? Need to check in view of importance to extracting couplings.
- How do we define signal and background?
  - at what point is the Higgs boson just another SM contribution?

Notation

$$\mathcal{A}_{\text{full}} = \delta^{a_1 a_2}\left(\frac{g_w^4 g_s^2}{16\pi^2}\right)\mathcal{P}_W(s_{34})\mathcal{P}_W(s_{56})\,\underbrace{[2\,\mathcal{A}_{\text{massless}} + \mathcal{A}_{\text{massive}}}_{\mathcal{A}_{\text{box}}} + \mathcal{A}_{\text{Higgs}}]$$

- Background only: $\sigma_B \longrightarrow \left|\mathcal{A}_{\text{box}}\right|^2$
- Signal only: $\sigma_H \longrightarrow \left|\mathcal{A}_{\text{Higgs}}\right|^2$

- This is the usual approach. To include the effect of interference define:

$$\sigma_i \longrightarrow 2\mathrm{Re}\left(\mathcal{A}_{\text{Higgs}}\mathcal{A}^*_{\text{box}}\right)$$

- Cross section in the presence of the Higgs, i.e. including also the interference:

$$\sigma_{H,i} \;=\; \sigma_H + \sigma_i$$

- Can then compare results for σ_H and $\sigma_{H,i}$.

Analyzing the interference

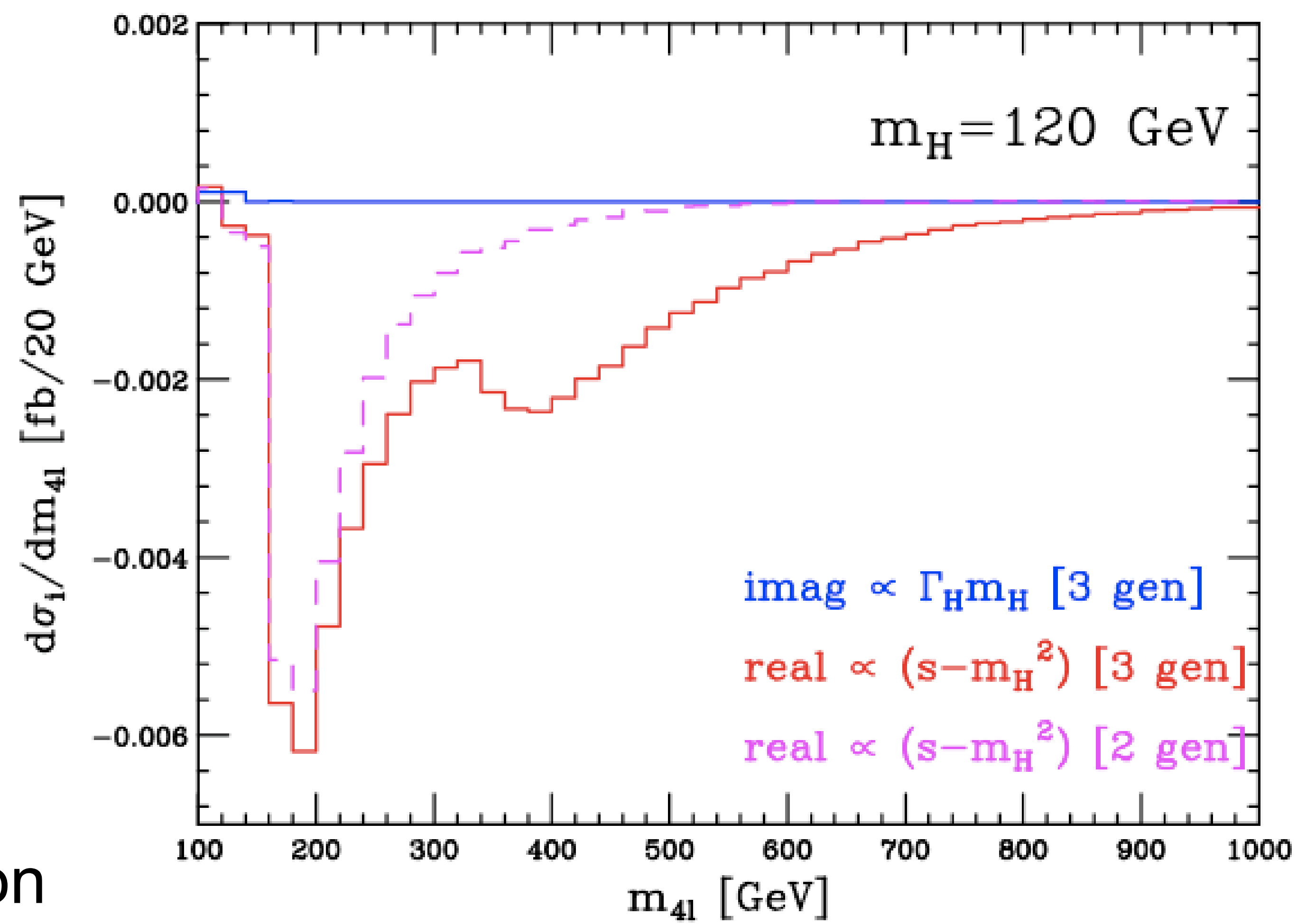
- Separate interference by Re and Im parts of propagator:

$$\delta\sigma_i = \frac{(\hat{s}-m_H^2)}{(\hat{s}-m_H^2)^2+m_H^2\Gamma_H^2}\,\mathfrak{Re}\left\{2\widetilde{\mathcal{A}}_{\text{Higgs}}\mathcal{A}^*_{\text{box}}\right\} + \frac{m_H\Gamma_H}{(\hat{s}-m_H^2)^2+m_H^2\Gamma_H^2}\,\mathfrak{Im}\left\{2\widetilde{\mathcal{A}}_{\text{Higgs}}\mathcal{A}^*_{\text{box}}\right\}$$

- For our light Higgs the second term is negligible.

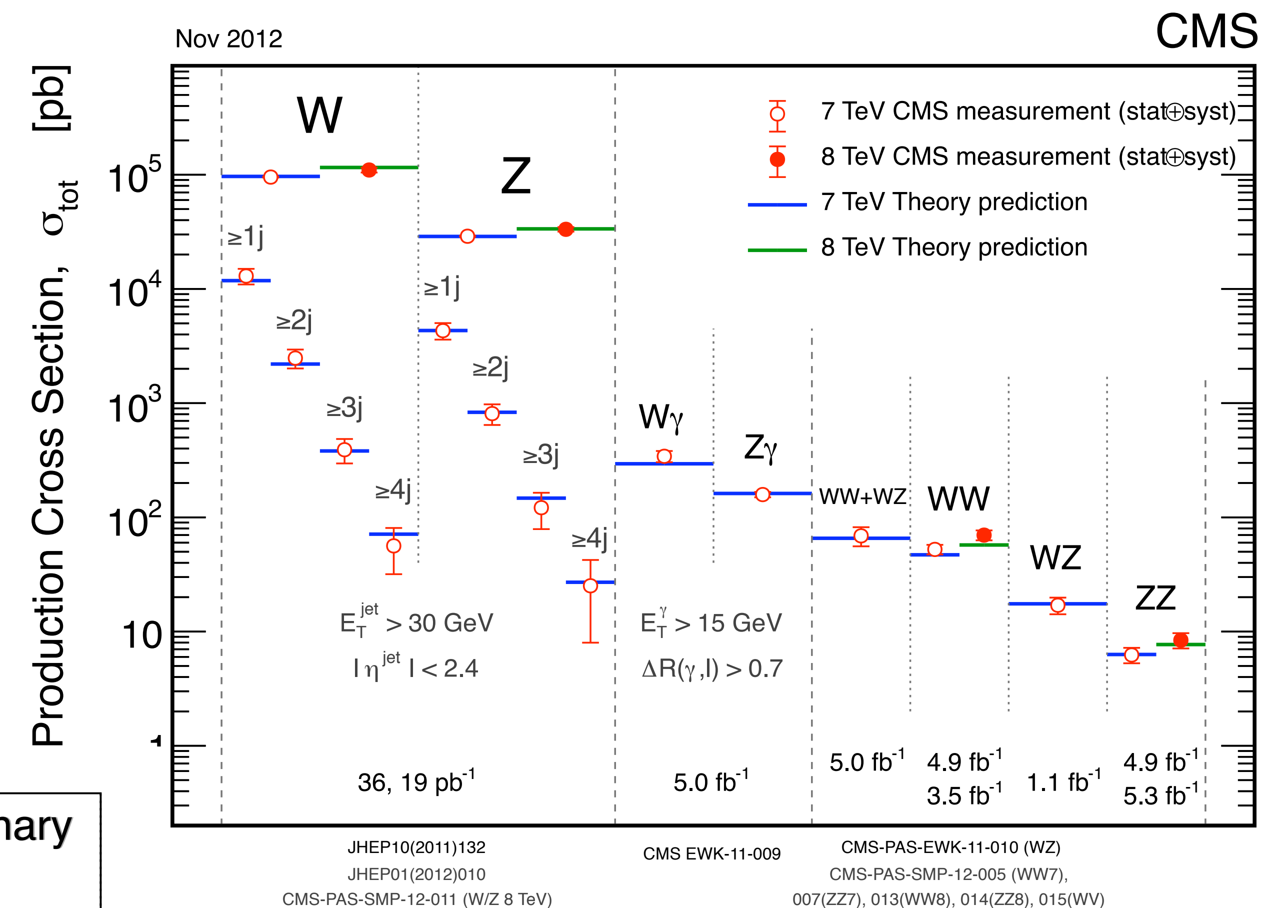
- If the full *s*-dependence of the first term can be represented by factor from the propagator, it should vanish on integration (odd about the Higgs mass).
    - but *s*-dependence is more complicated because the box diagrams favour large invariant masses (W pairs).

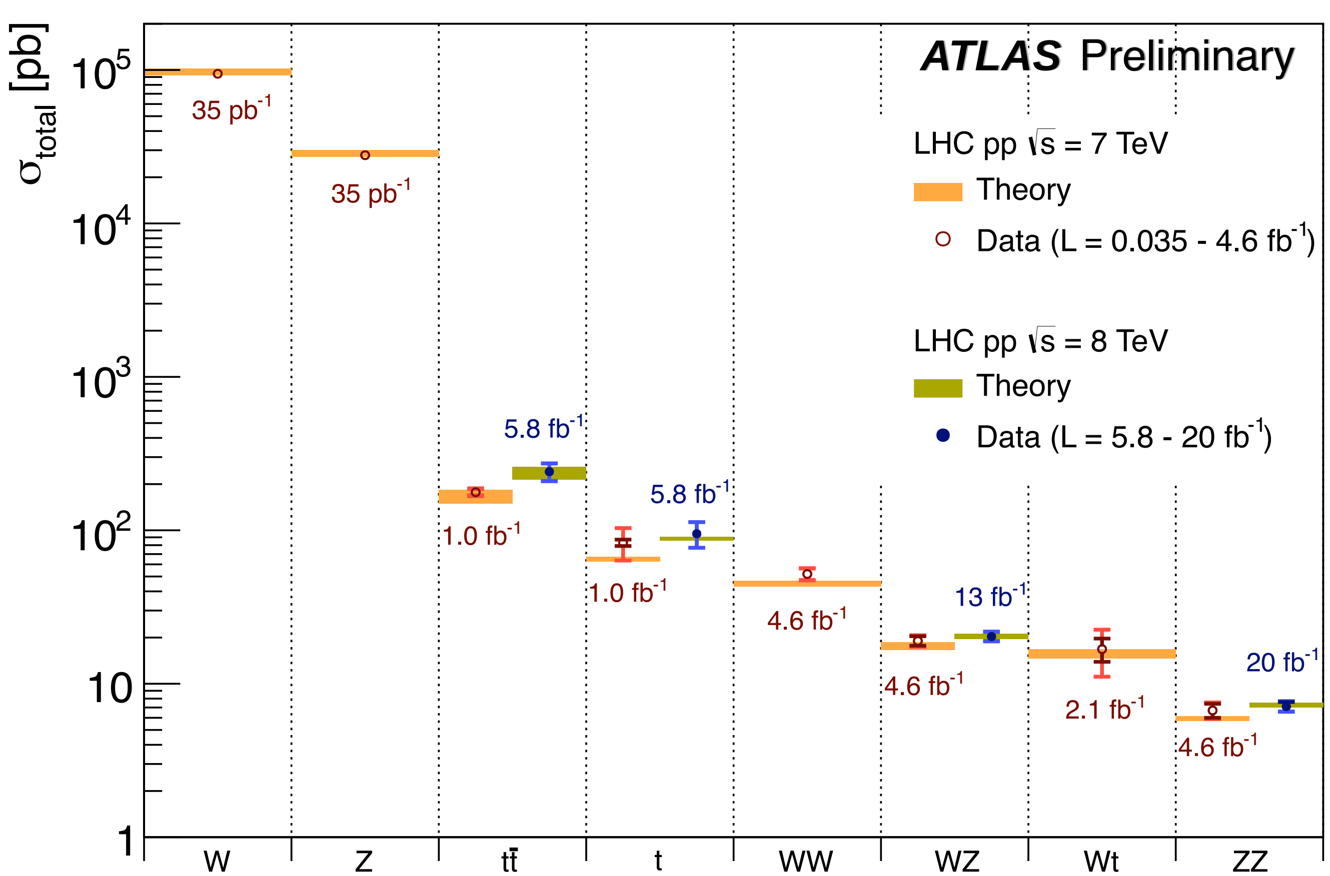
- Long destructive tail required by unitarity; integrated contribution significant, (negative) 10-15%.



Vector bosons: experimental summary

Good consistency with expectations of NNLO (W/Z) and NLO (dibosons) for all processes in both experiments.



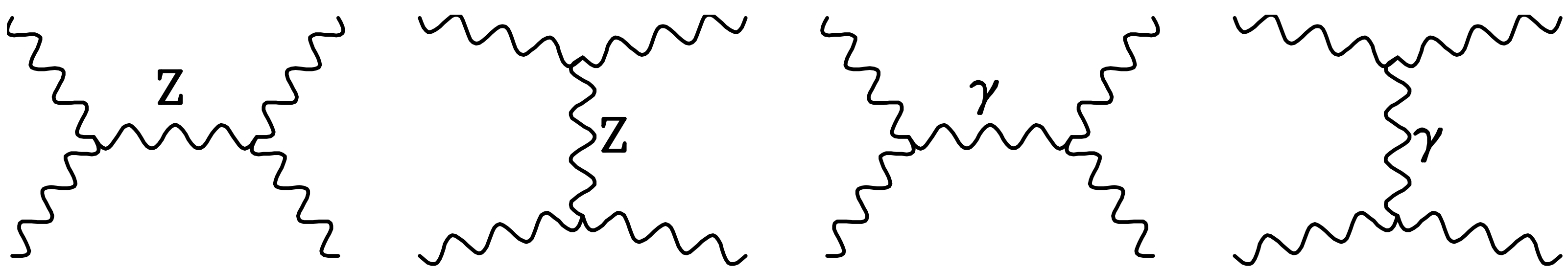


Slight exception: WW has a small error and looks high throughout.

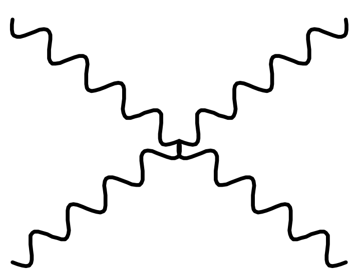
Vector boson scattering

- One way of probing the electroweak sector further is through vector boson scattering.
- Simplest to consider the amplitudes not a hadron collider but in the pure scattering process:

$$W^+(p_+) + W^-(p_-) \rightarrow W^+(q_+) + W^-(q_-)$$



(a) (b) (c) (d)



(e)

Five diagrams all involving self-couplings of the vector bosons

High-energy limit (again)

- Once again consider the high-energy behaviour, concentrating on leading behaviour given by the scattering of longitudinal W bosons.
- Incoming W's along the *z*-axis:

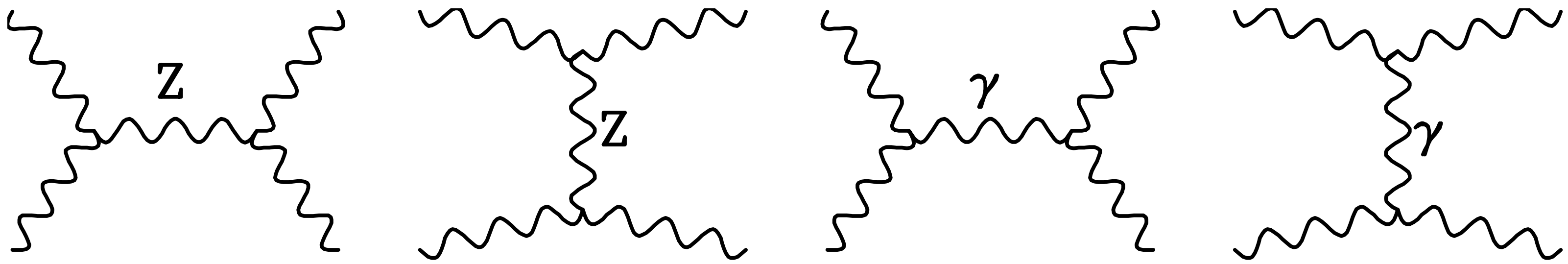
$$\begin{aligned} p_\pm &= (E, 0, 0, \pm p)\ , \\ q_\pm &= (E, 0, \pm p \sin\theta, \pm p \cos\theta) \end{aligned}$$

and longitudinal polarizations a slight generalization of previous form:

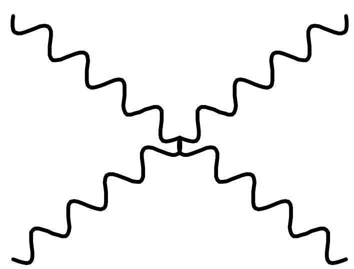
$$\begin{aligned} \varepsilon_L(p_\pm) &= \left(\frac{p}{M_W}, 0, 0, \pm\frac{E}{M_W}\right)\ , \\ \varepsilon_L(q_\pm) &= \left(\frac{p}{M_W}, 0, \pm\frac{E}{M_W}\sin\theta, \pm\frac{E}{M_W}\cos\theta\right) \end{aligned}$$

- Use these to calculate the form of the diagrams in the high-energy limit, i.e. dropping terms without factor of p^2/m_W^2.

Result



(a) (b) (c) (d)



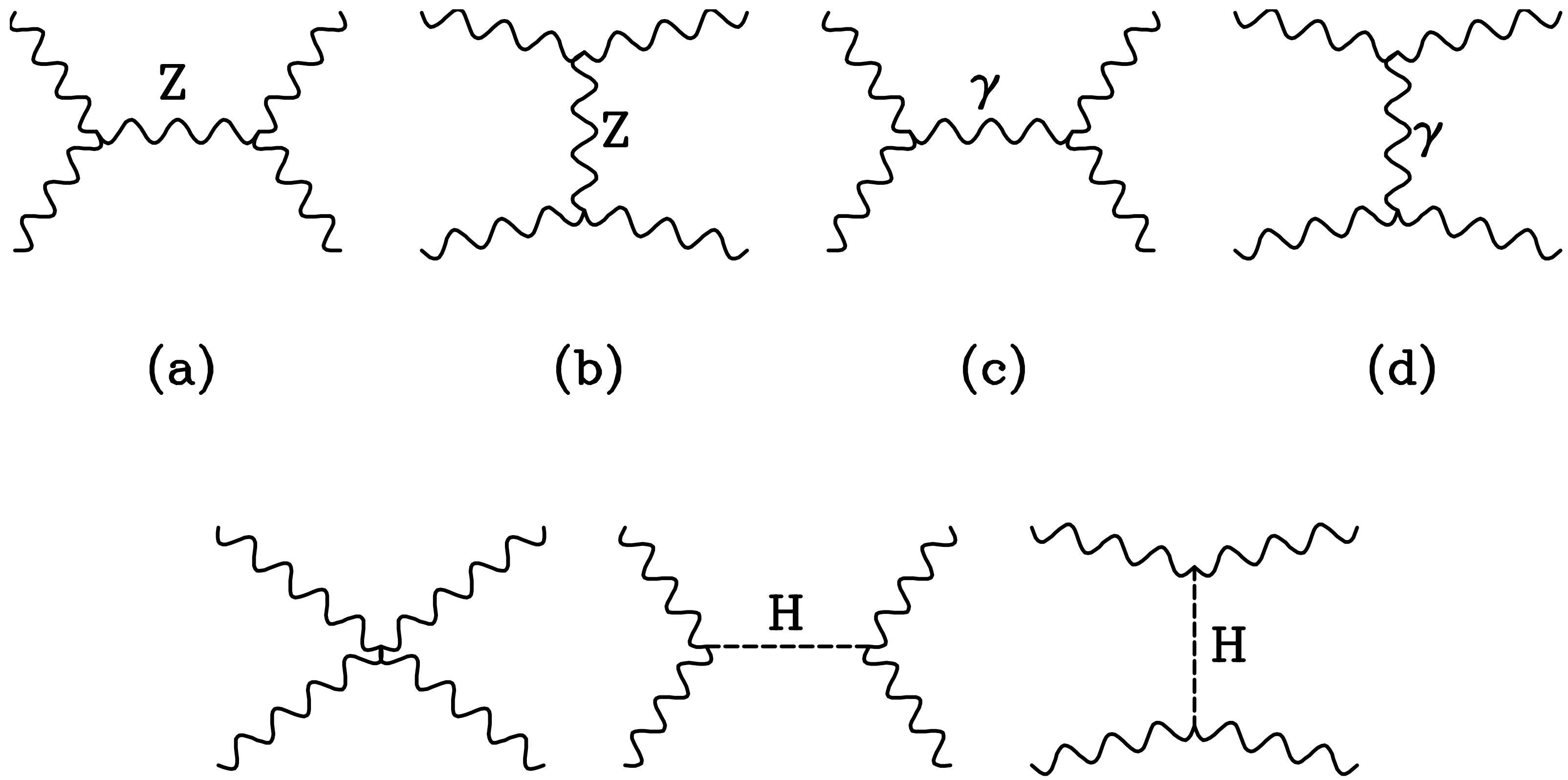
(e)

Leading term (p^4) cancels, but p^2 remains:

$$T^e = g_w^2 \left\{ \frac{p^4}{M_W^4} \left[-3 + 6\cos\theta + \cos^2\theta \right] + \frac{p^2}{M_W^2} \left[-4 + 6\cos\theta + 2\cos^2\theta \right] \right\}$$

$$T^{a-d} = g_w^2 \left\{ \frac{p^4}{M_W^4} \left[3 - 6\cos\theta - \cos^2\theta \right] + \frac{p^2}{M_W^2} \left[\frac{9}{2} - \frac{11}{2}\cos\theta - 2\cos^2\theta \right] \right\}$$

Result (continued)



(a) (b) (c) (d)

(e) (f) (g)

Cancellation now complete

$$T^{f-g} = g_w^2 \left\{ \frac{p^2}{M_W^2} \left[-\frac{1}{2} - \frac{1}{2}\cos\theta \right] - \frac{M_H^2}{4M_W^2} \left[\frac{s}{s-M_H^2} + \frac{t}{t-M_H^2} \right] \right\}$$

$$T^e = g_w^2 \left\{ \frac{p^4}{M_W^4} \left[-3 + 6\cos\theta + \cos^2\theta \right] + \frac{p^2}{M_W^2} \left[-4 + 6\cos\theta + 2\cos^2\theta \right] \right\}$$

$$T^{a-d} = g_w^2 \left\{ \frac{p^4}{M_W^4} \left[3 - 6\cos\theta - \cos^2\theta \right] + \frac{p^2}{M_W^2} \left[\frac{9}{2} - \frac{11}{2}\cos\theta - 2\cos^2\theta \right] \right\}$$

Discussion

- As a result, WW scattering amplitude does not diverge at high-energy.
  - however, it may still be too large for perturbative unitarity to hold
- Can examine using a partial-wave analysis.

Lee, Quigg and Thacker (1977)

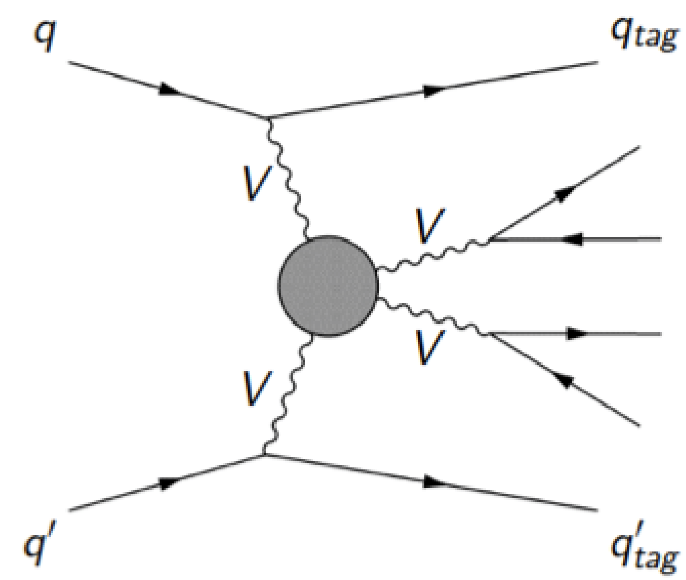
- Looking at all channels of vector boson scattering and requiring unitarity results in a constraint on the Higgs boson mass:

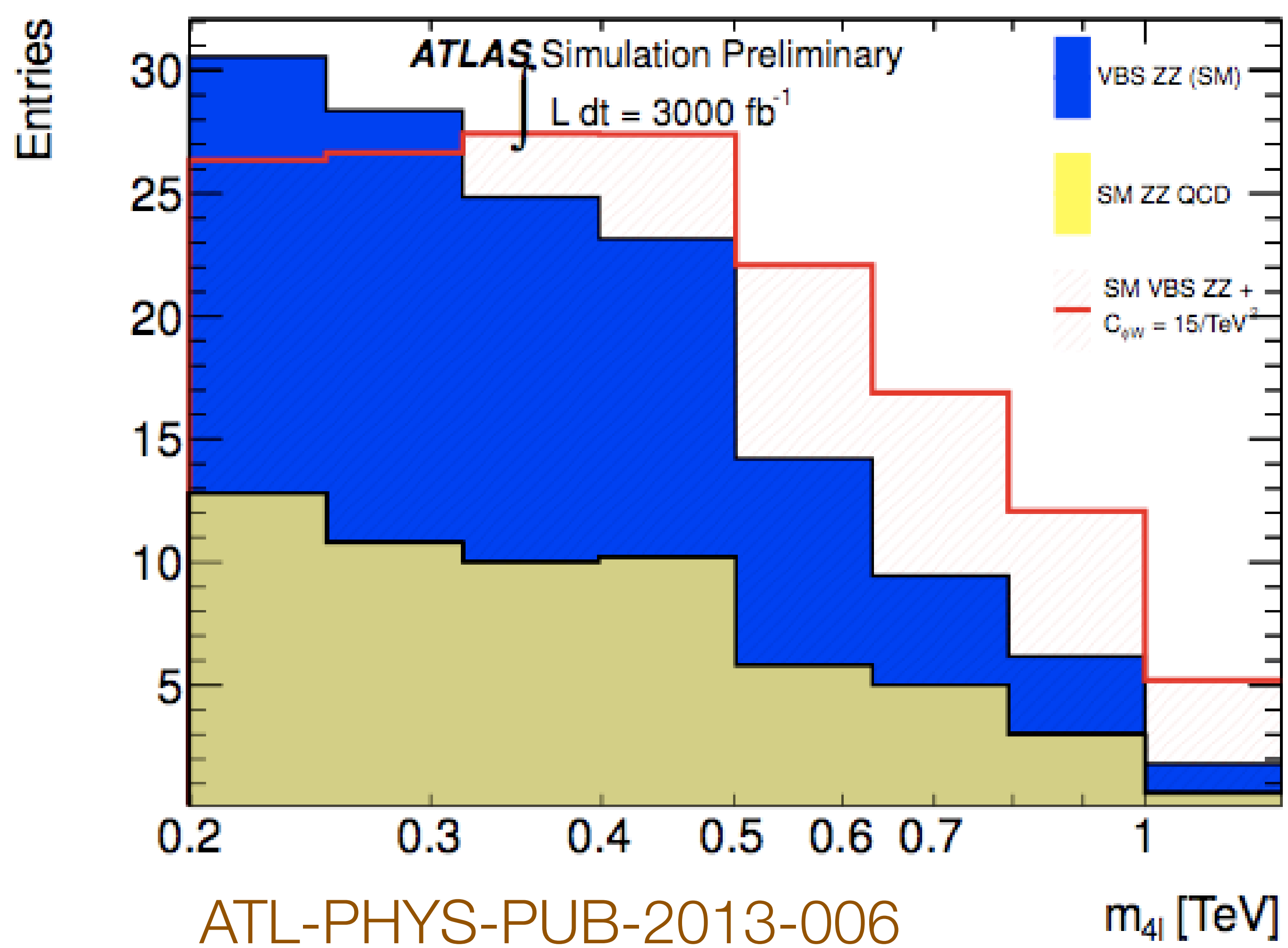
$$M_H < \left(\frac{8\sqrt{2}\pi}{3G_F}\right)^{\frac{1}{2}} \approx 1\ \mathrm{TeV}$$

- Observation of a Higgs boson violating this bound would have meant strong interactions of W,Z bosons that could not be described perturbatively.
- Even with a light Higgs, it is possible that it is not entirely responsible for the unitarization at high energies
  - essential to probe vector boson scattering to look for anomalous couplings/hints of new particles.

Recent study

- Like vector-boson fusion: induce scattering in association with two forward jets.
- Sensitivity to operators not probed in diboson production ($C_{\Phi W}$ here).
- σ_{SM} ~ 0.5 pb (w/o decays), need v.high luminosity.





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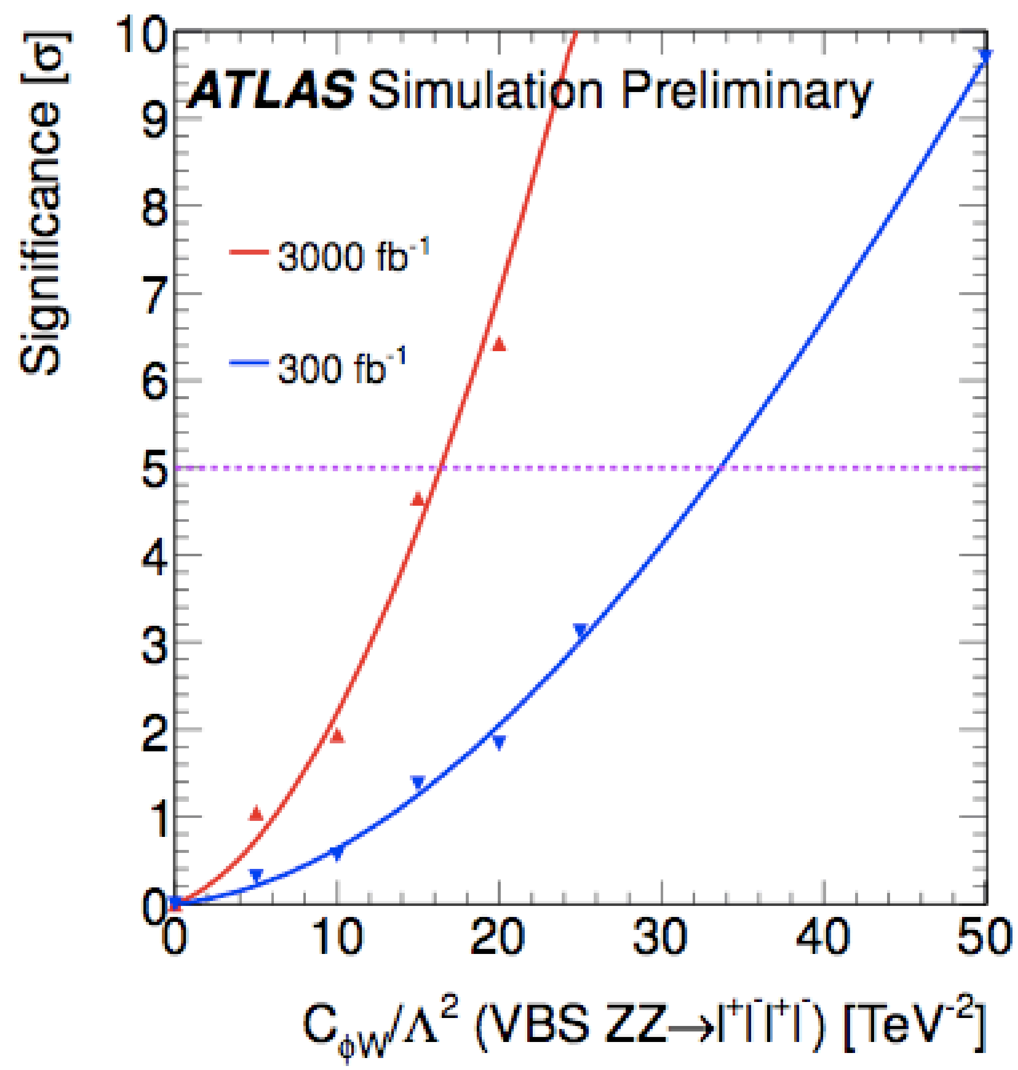


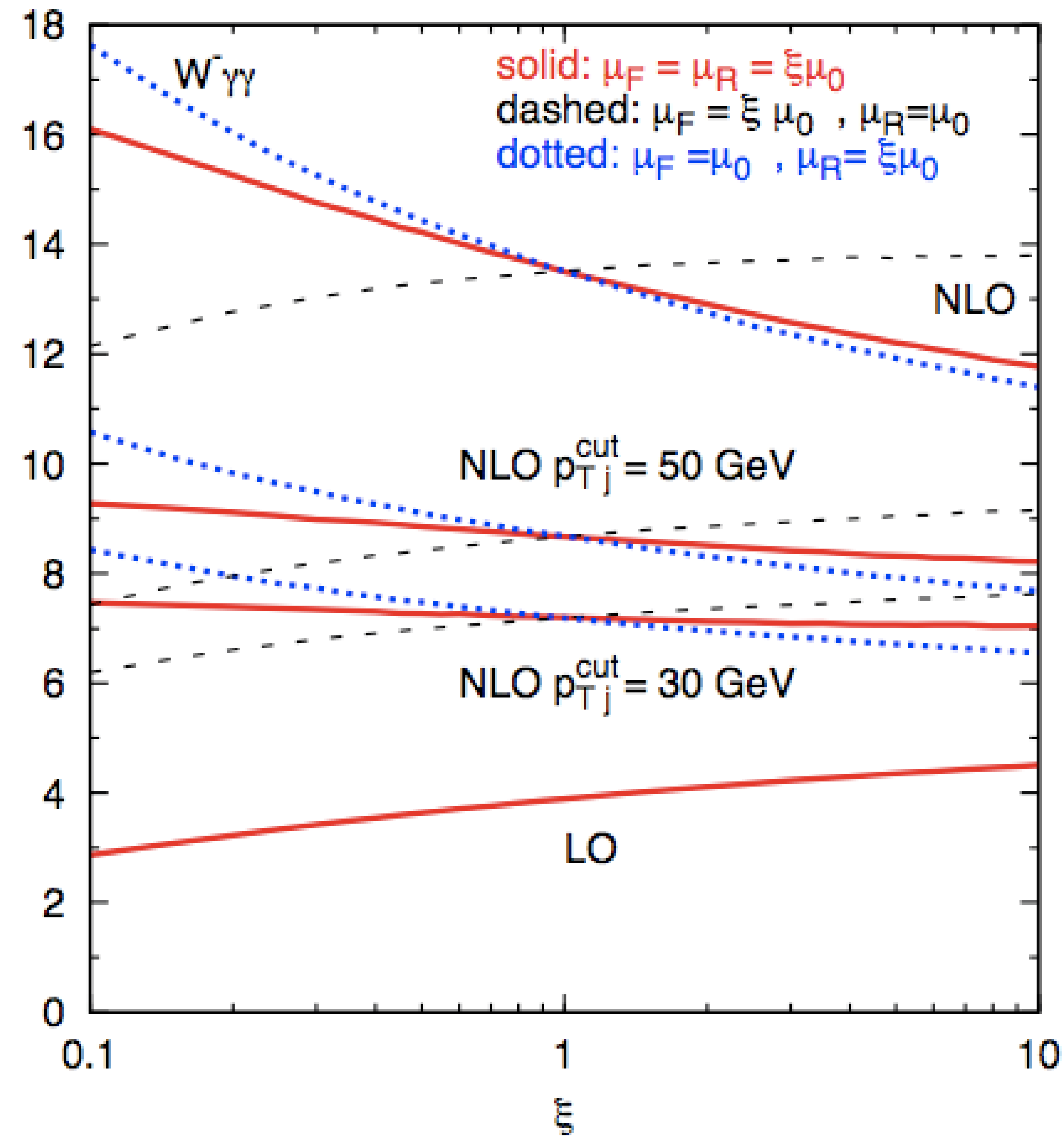
Tri-boson production

- Cross sections very small: after including decays and cuts, cross sections are in the region of tens of femtobarns (at most).
- All modes available in VBFNLO, Zγγ in MCFM.
- Example: Wγγ scale dependence (VBFNLO).

Large enhancement due to gluon flux

Even after vetoing real radiation, significant enhancement due to RAZ

Bozzi et al (2011)



- Era of tri-boson measurements just beginning at LHC.

Summary

- The importance of multi-boson production.
  - role of self-interactions (gauge structure) in taming high-energy behaviour
- Review of selected di-boson phenomenology.
  - radiation amplitude zero, jet-binning, aTGCs, interference
- Beyond inclusive di-boson measurements.
  - the importance of vector boson scattering