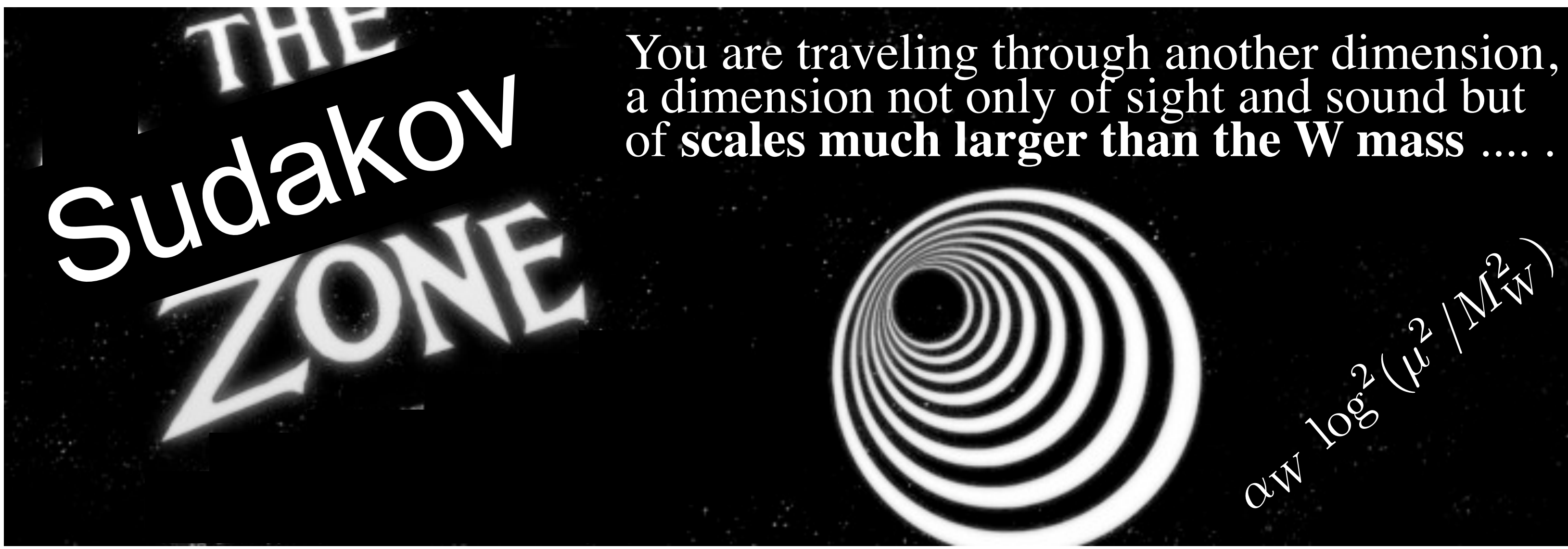
Electroweak Corrections at High Energies

Kalanand Mishra, *Fermilab*



Snowmass: Seattle Energy Frontier Workshop, July 2, 2013

Outline

- Introduction
  - What are EWK corrections, when/where they matter
- A survey of the most abundant processes at LHC for sensitivity to EWK corrections: at 8 TeV, 14 TeV, 33 TeV, and 100 TeV collider energies
  - inclusive jet, dijets
  - inclusive W/Z
  - W/Z+jets
  - Diboson (WW)
- Summary table

Definition

If experimental and PDF errors are < EWK corrections, then I'll call the measurement as being in the Sudakov zone. Typically need a few dozen events above 1 TeV to be in this zone.

When electroweak corrections are too strong

•EWK corrections become important in certain kinematic regimes

•At the ~TeV scale, they significantly modify production cross sections through Sudakov logs of order $\alpha_W \log^2(\mu^2/M_W^2)$

= 25*α_W @μ=1TeV

This typically exceeds ~10% of LO when μ is of order 1 TeV

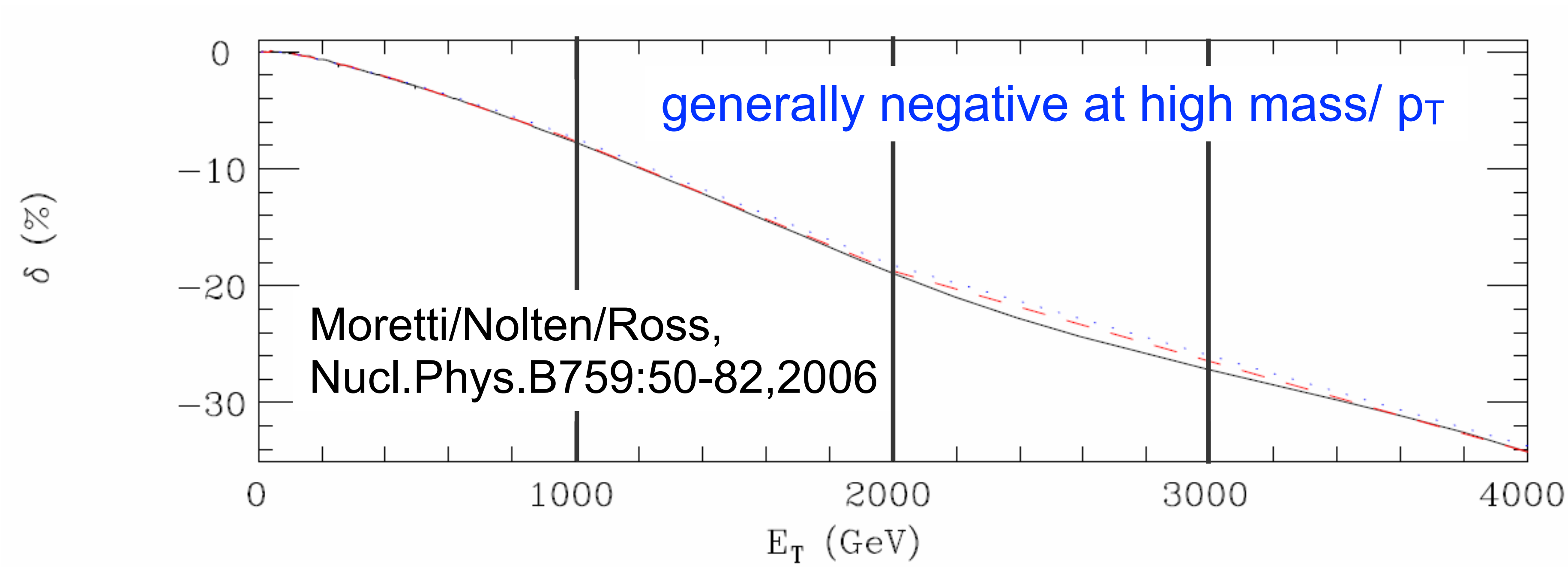
•We are now encountering LHC data where experimental precision at the TeV scale is of order 10%

Important not only for nominally electroweak processes, but for nominally QCD ones as well!

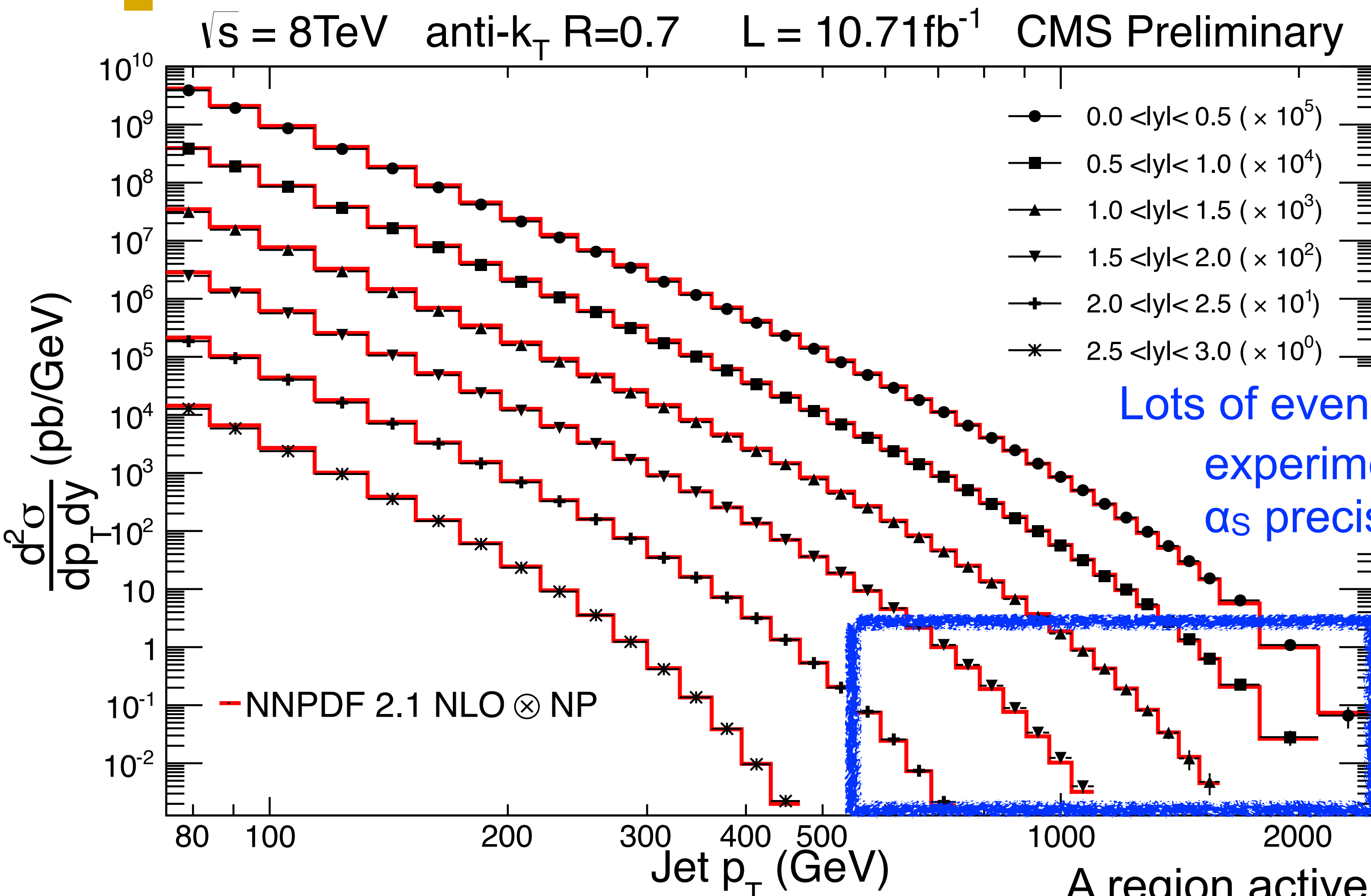
How big an effect we are talking about ?

Inclusive jet production at LHC

For inclusive jet production at 14 TeV, negative virtual contribution dominates over real emission at ~1 TeV and **cross section decreases from LO result** by ~20% at 2TeV



Are EWK corrections too strong for jets?



Lots of events at large $\hat{s}$, experimental & NLO α_S precision 10%

comparable to EWK corr.

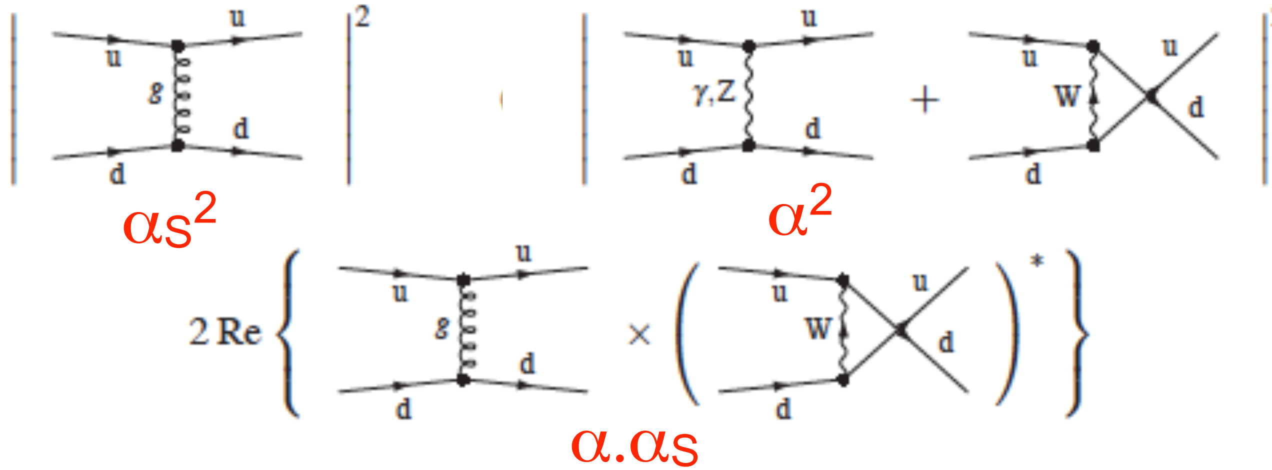
A region actively searched for BSM signals

https://cdsweb.cern.ch/record/1547589

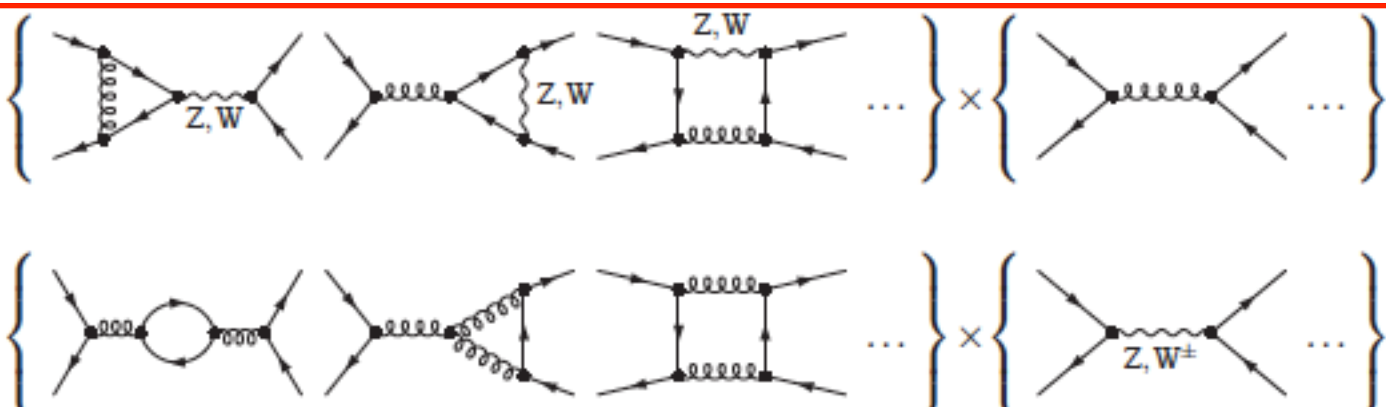
A classic example: EWK corr for dijet production

arXiv:1210.0438,
arXiv:1306.6298

Tree-level diagrams
(+ve contribution)

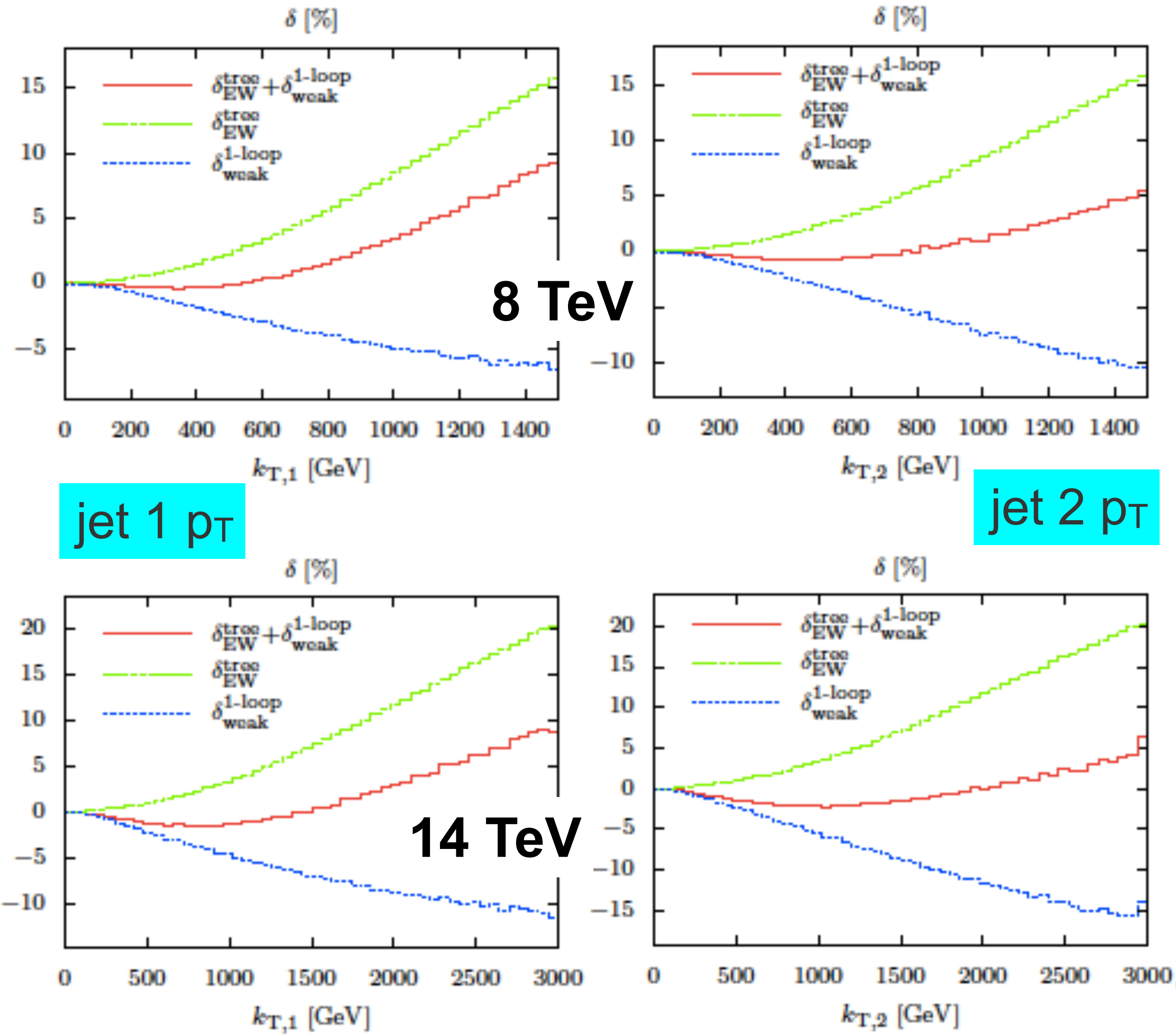


Loop diagrams
(−ve contribution, virtual, Sudakov)



Although negligible for integrated xsec, Sudakov corrections can reach 10−20% for TeV jets in interesting kin regimes

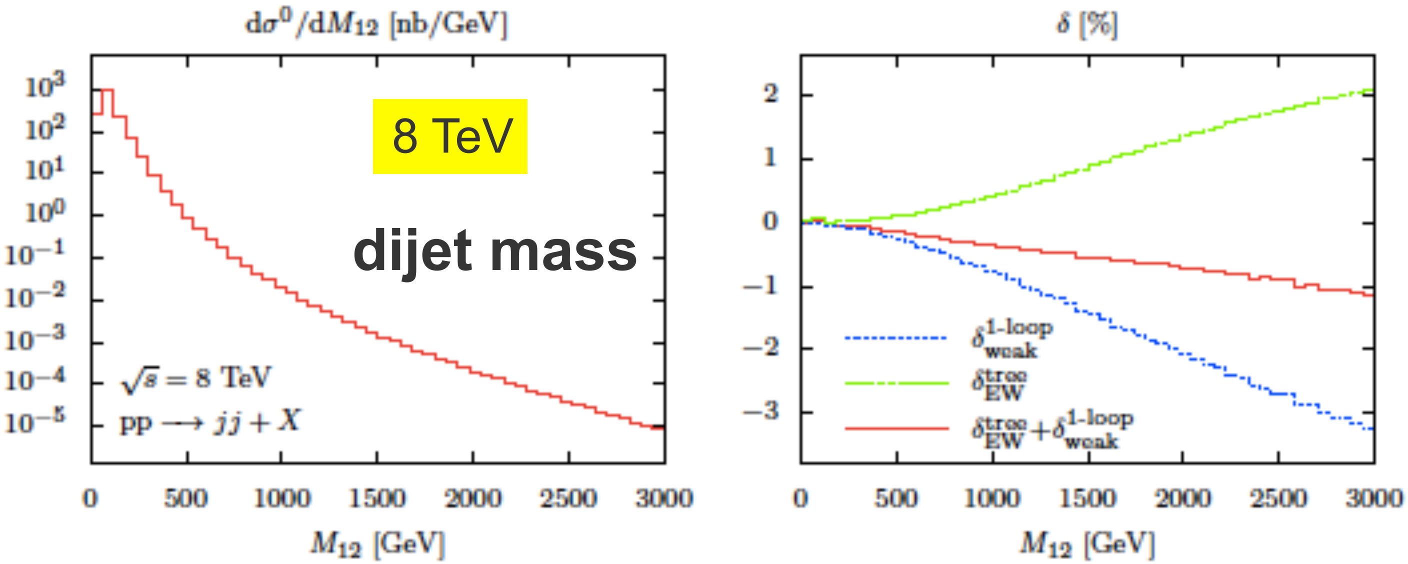
Dijet expectation at 8 TeV and 14 TeV



arXiv:1210.0438

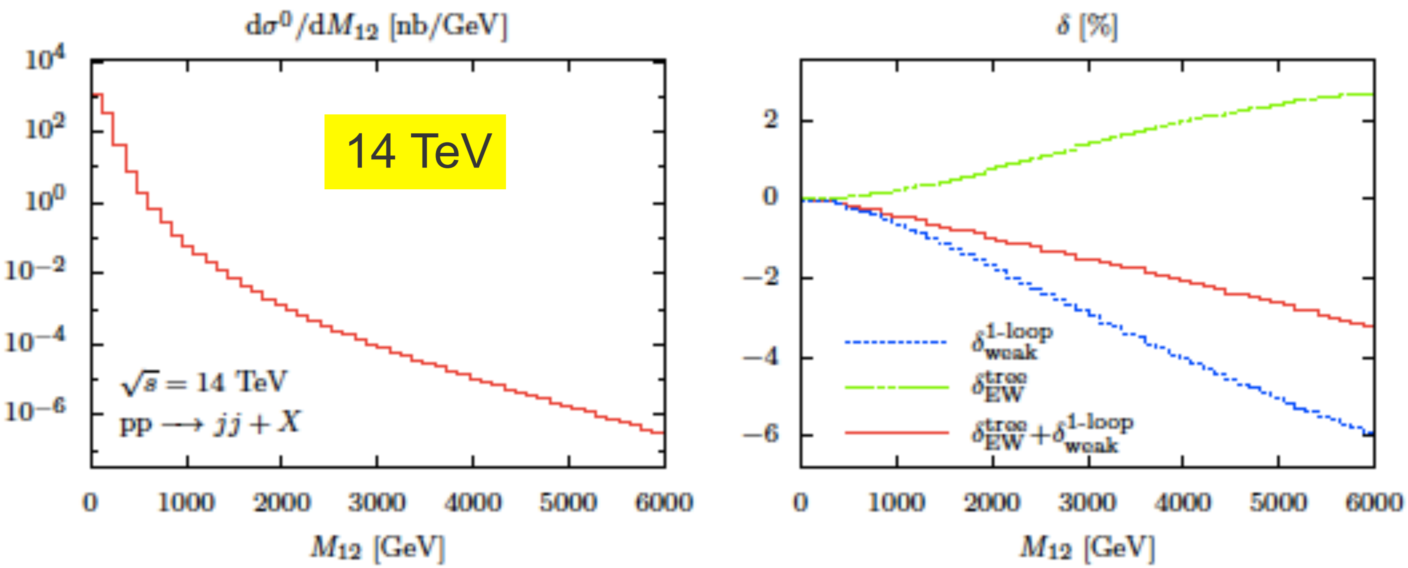
Sudakov virtual correction is large, although the net EWK correction is small

Dijet expectation at 8 TeV and 14 TeV



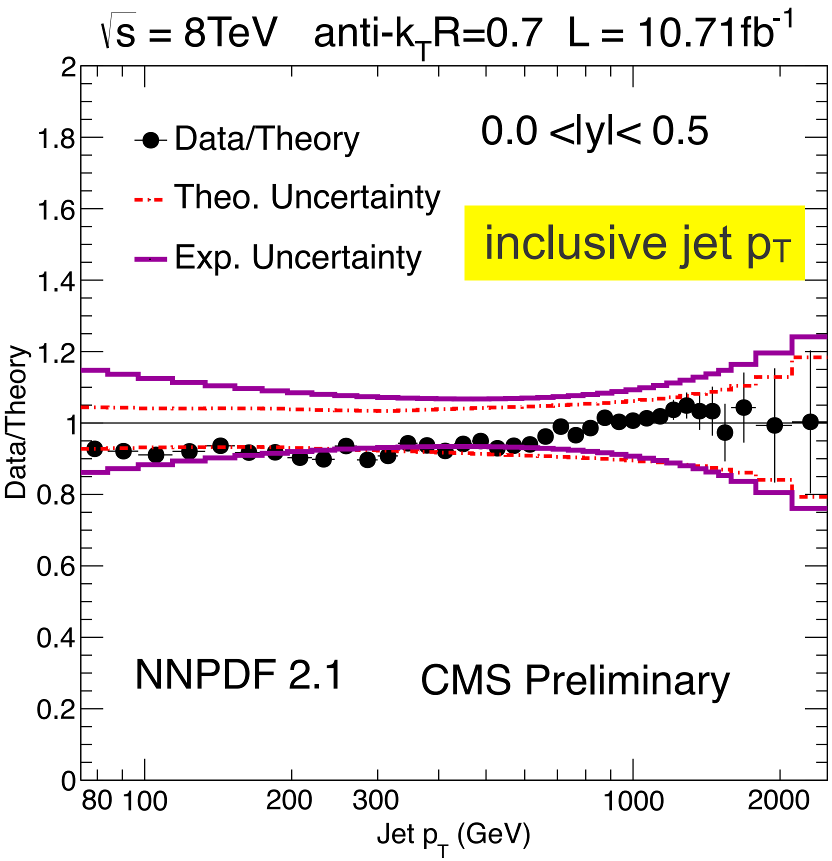
Typically we are interested in low y*, where the correction can be even larger.

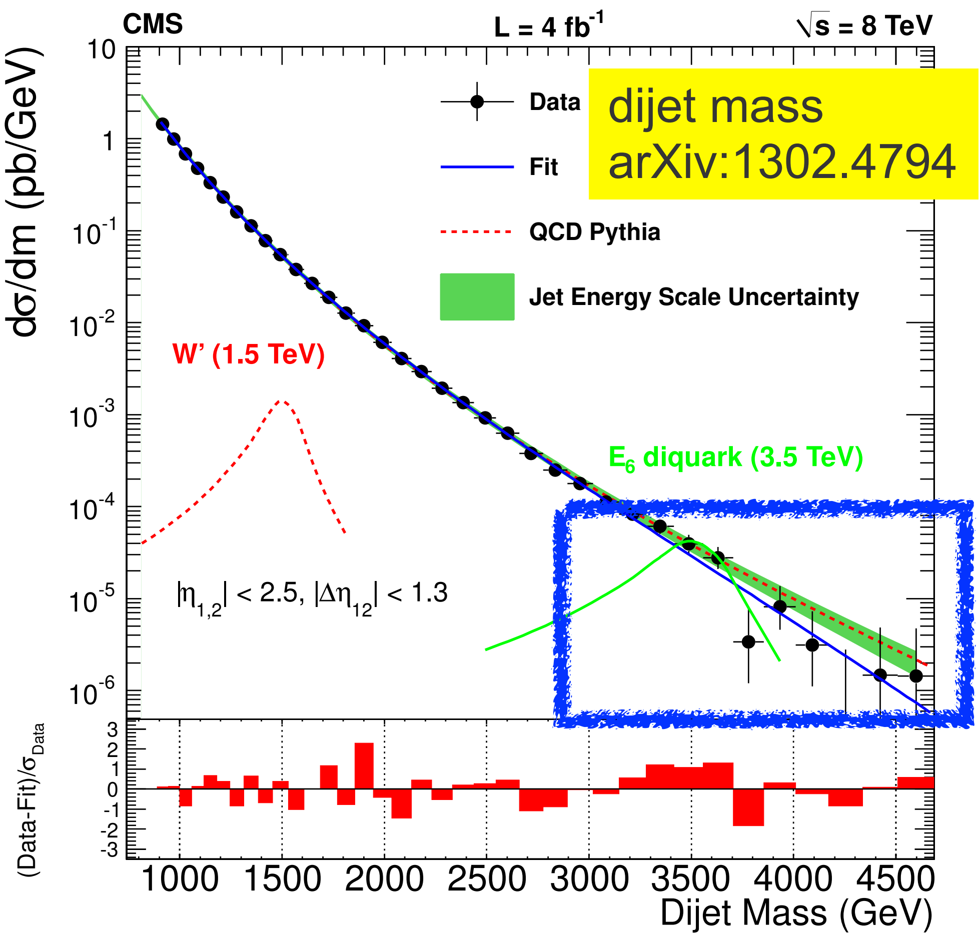
arXiv:1210.0438



See the paper for plots of individual y* bins

Too strong for jets? At today's precision, yes!

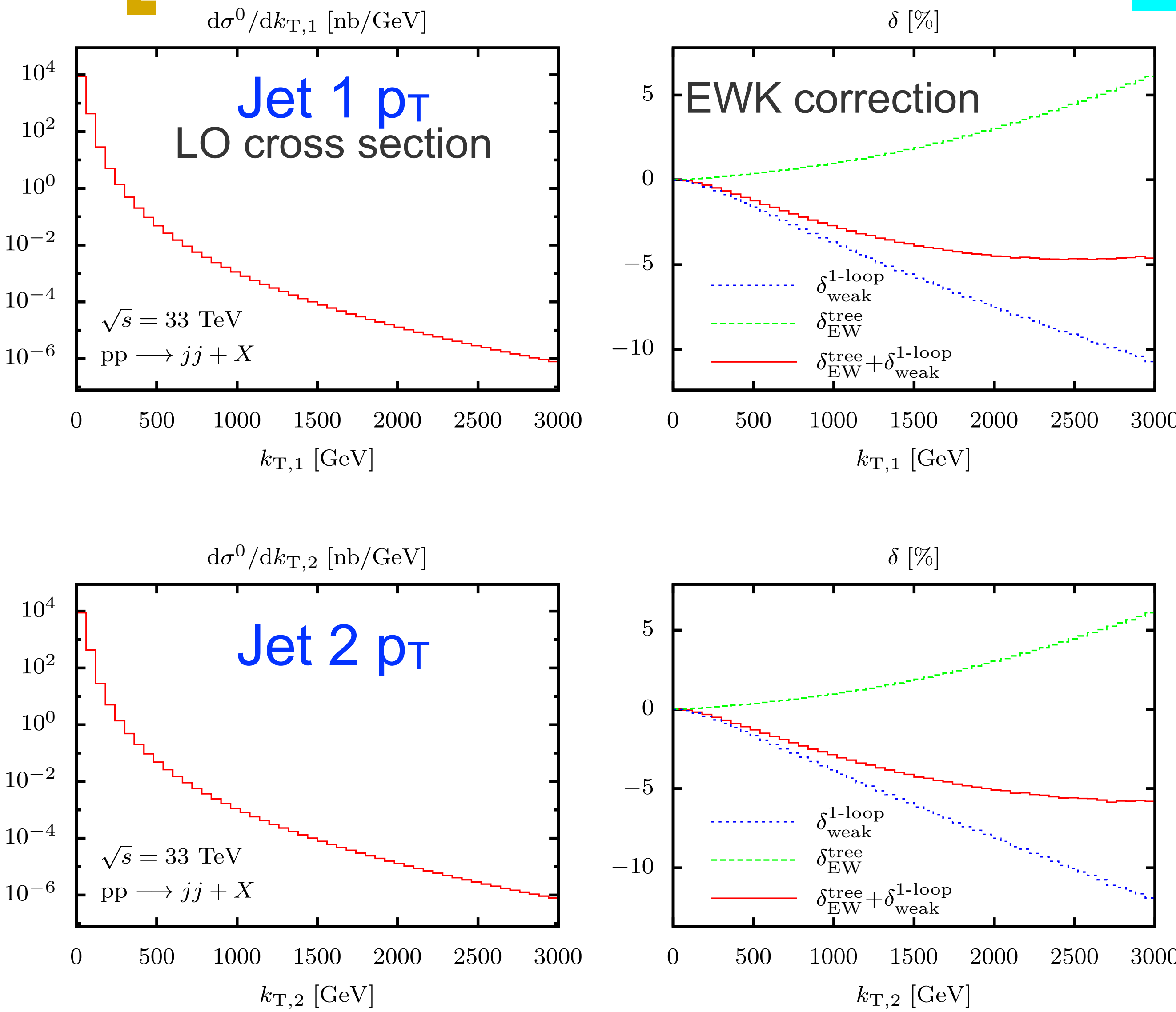




- Theory and experimental error for ~2(4) TeV jets(dijets) is ~10%
  - -Comparable to the size of EWK corrections

So, what we expect at 33 TeV?

Provided by Alexander Huss & Stefan Dittmaier

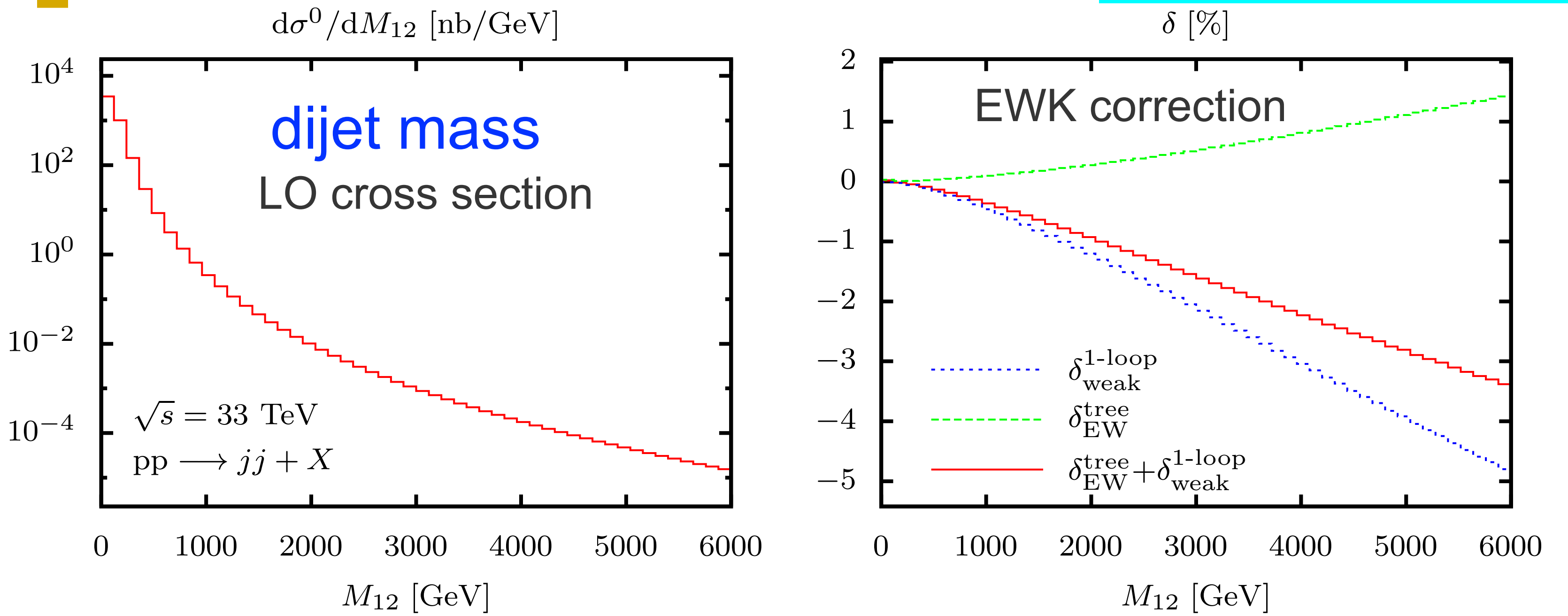


- Weak 1-loop corr not so dependent on collider energy in the case of p_T distribution for which the tails are dominated by the Sudakov regime.
- Tree-level corr are dependent on collider energy due to 4-quark subprocesses that gain in importance at higher E.

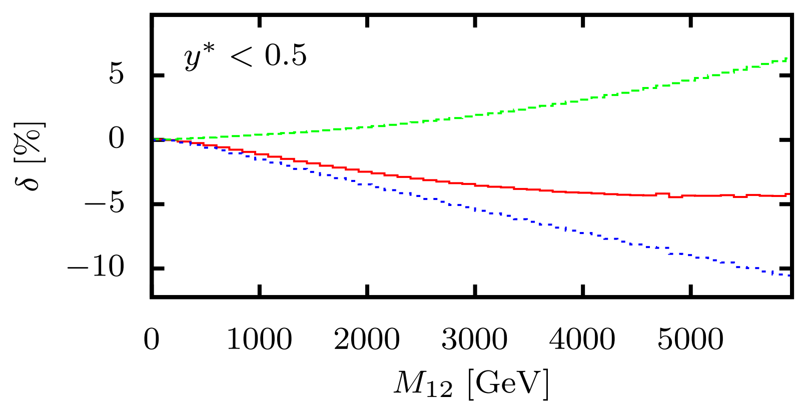
arXiv:1306.6298

So, what we expect at 33 TeV?

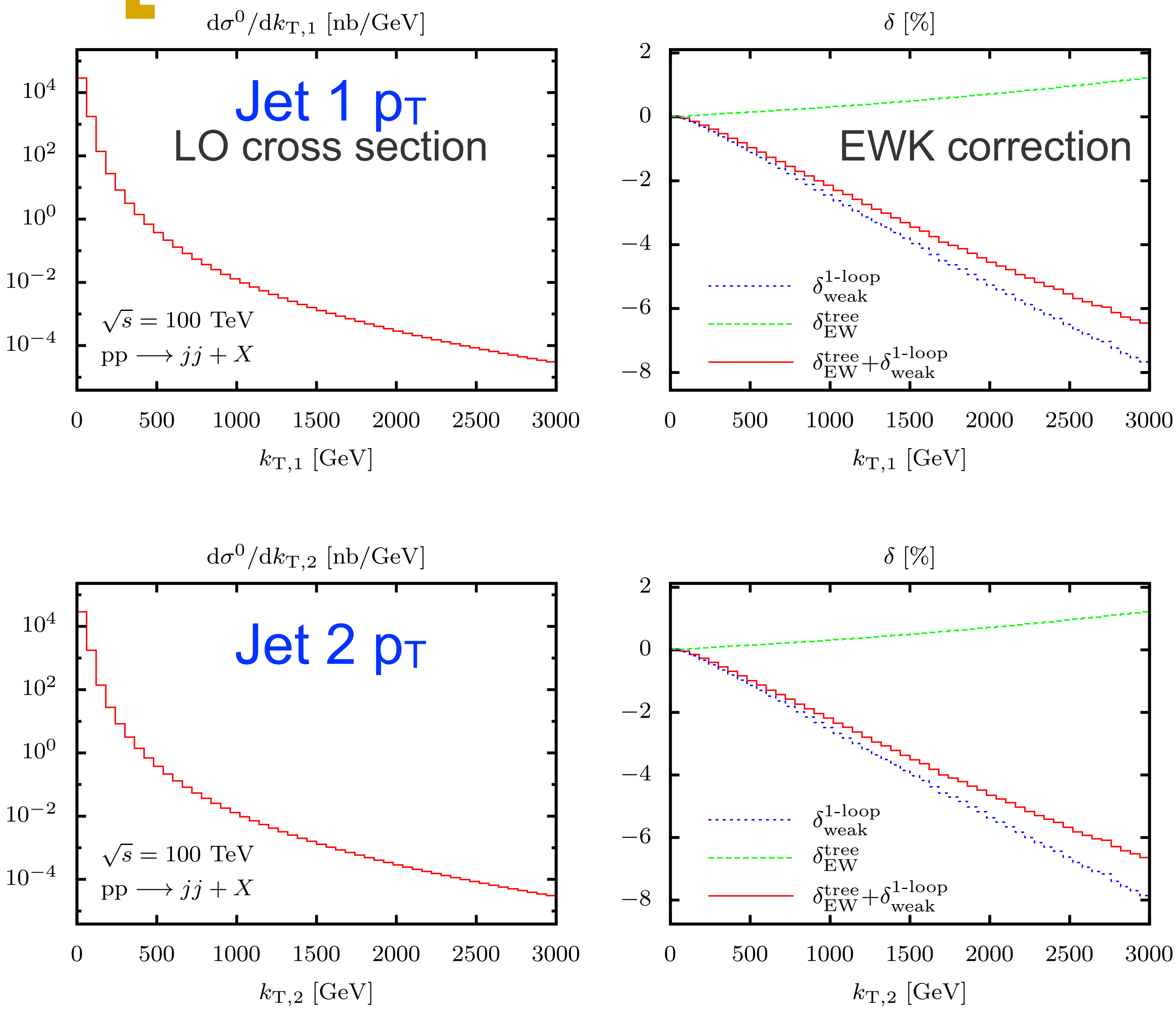
Provided by Alexander Huss & Stefan Dittmaier



For M_{jj} the energy dependence is stronger, since not probing pure Sudakov regime (not solely described by ythe universal Sudakov logarithms). However, the lowest y* bins (in Sudakov regime) are less dependent on the energy & show a similar behavior to the p_T distributions.



At 100 TeV

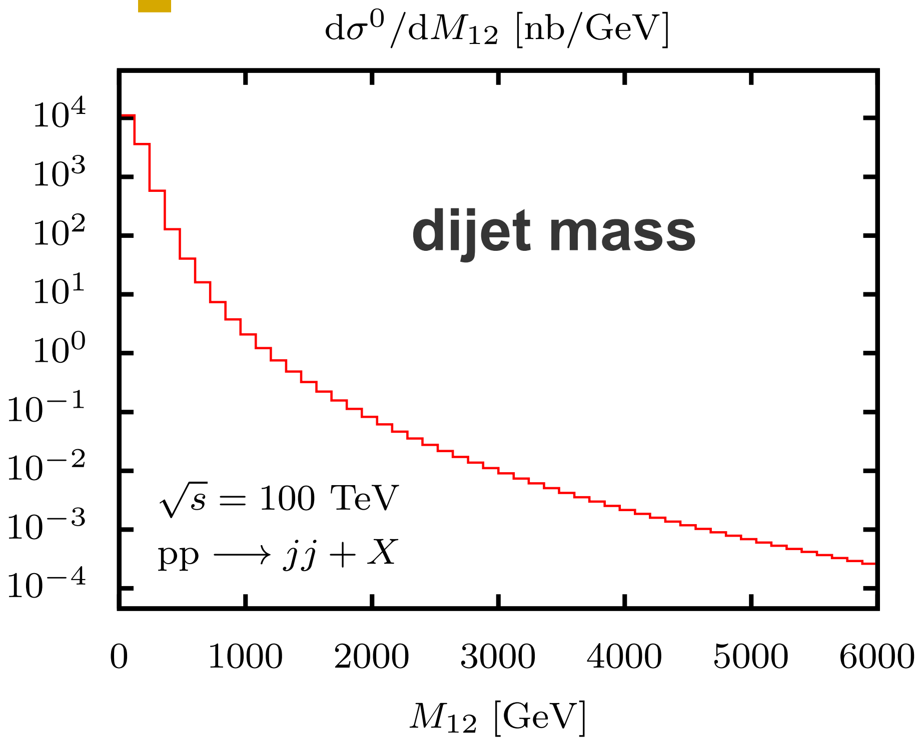


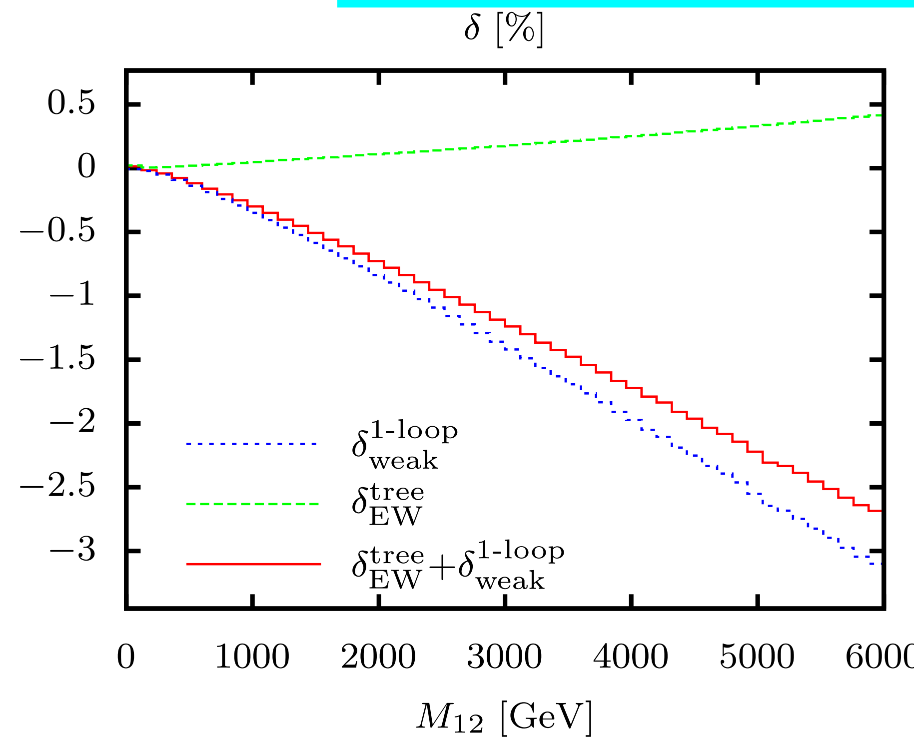
Provided by Alexander Huss & Stefan Dittmaier

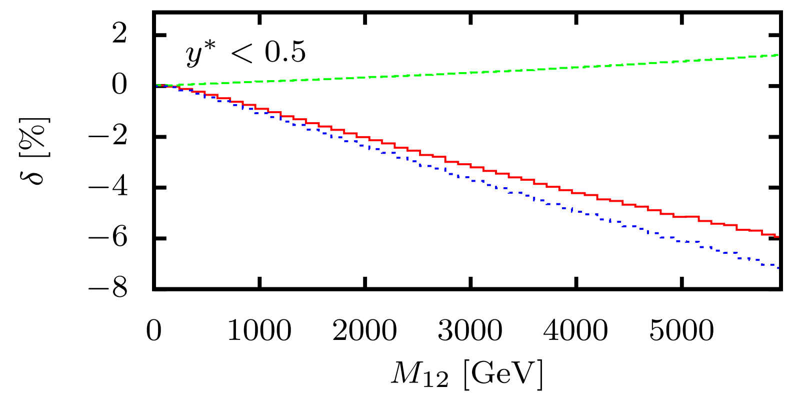
Very similar to the 33 TeV result

At 100 TeV

Provided by Alexander Huss & Stefan Dittmaier

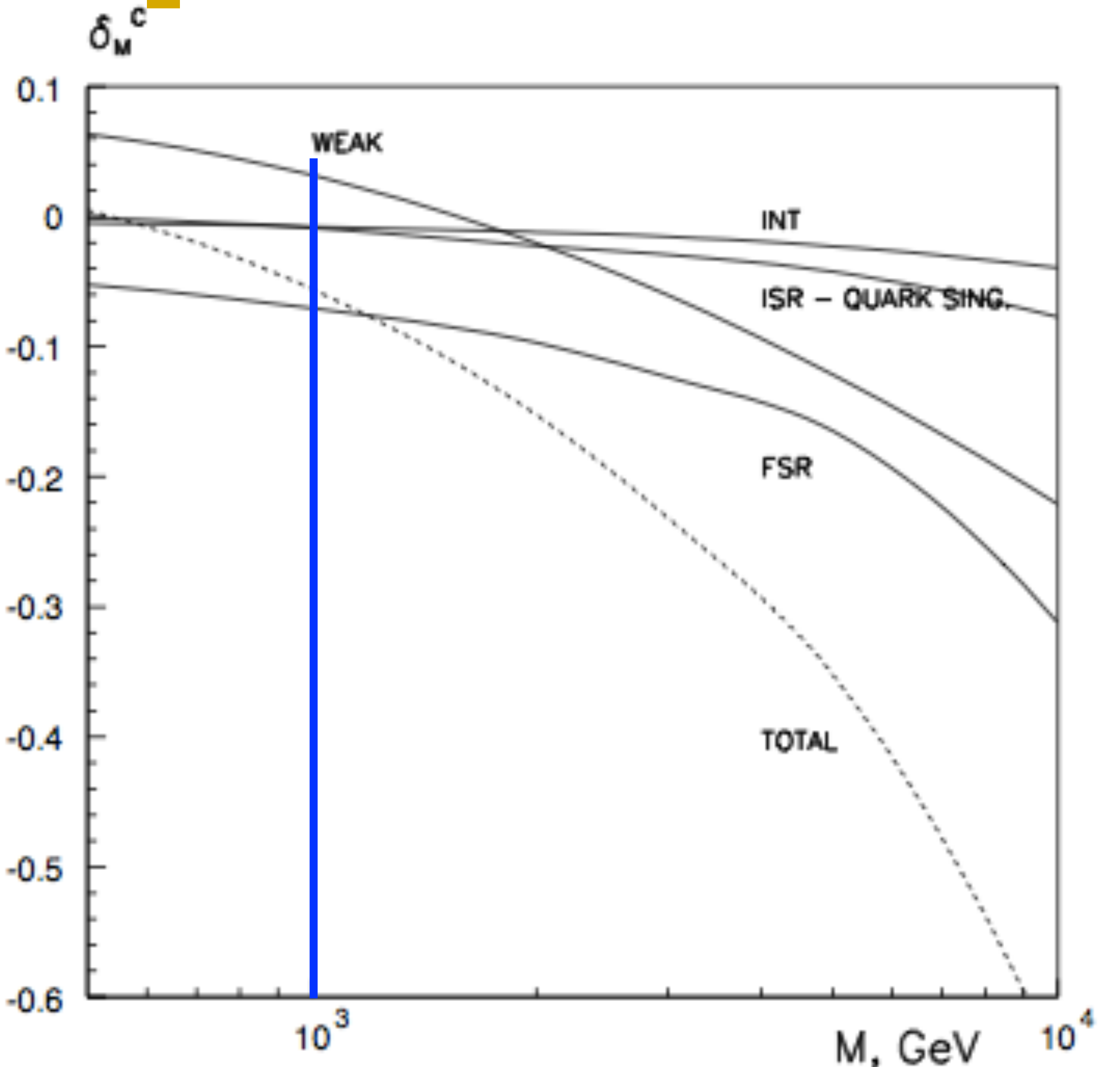






Very similar to the 33 TeV result

What about electroweak processes

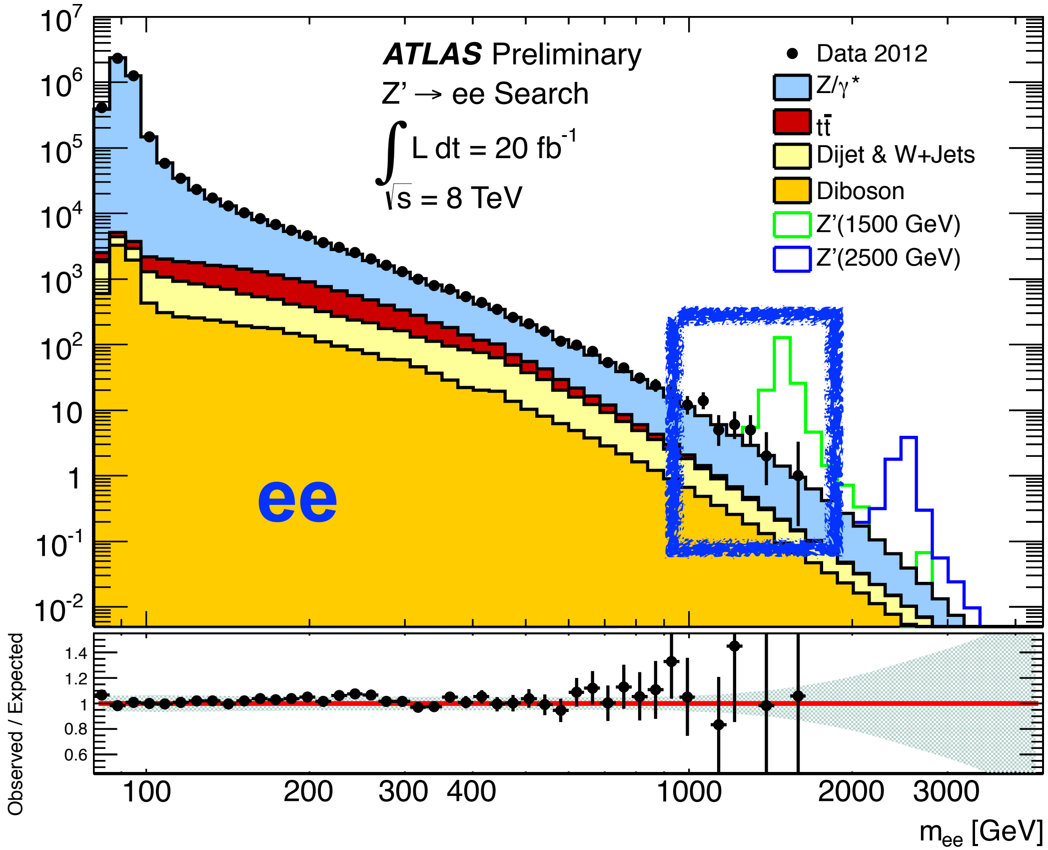


Zykunov, arXiv: hep-ph/0702-203

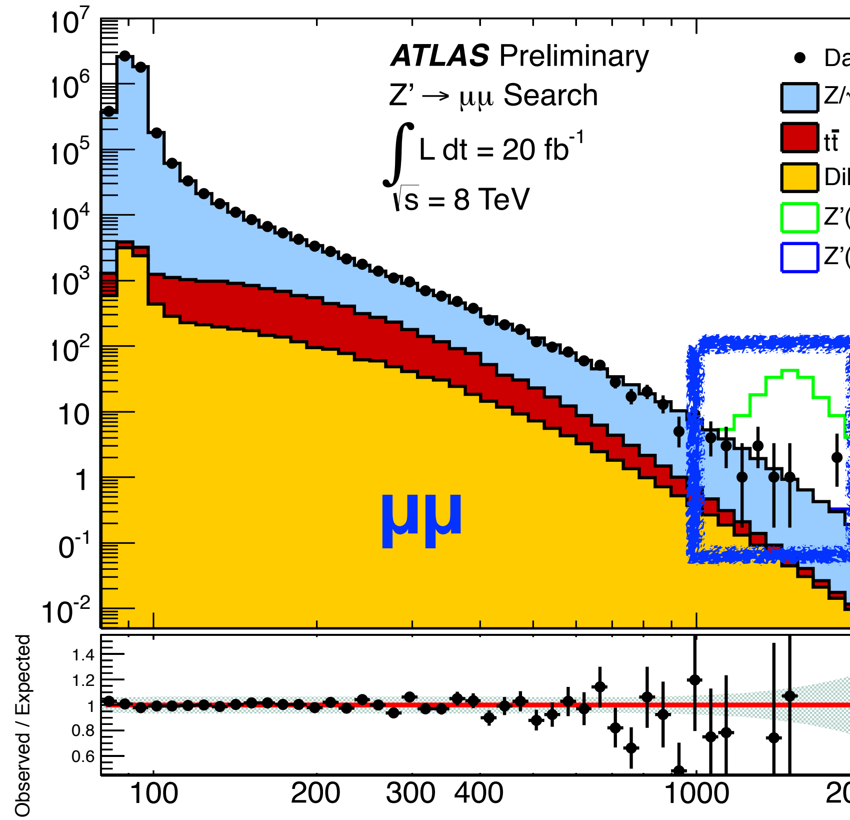
Almost everything we could measure in 2010 (jets, photons, W, Z) has entered the "Sudakov zone" in 2012.

As in the case of inclusive jet, the QCD NLO correction (+ve) compensates for EWK correction (−ve).

Too strong for Z? Yes, in some cases.

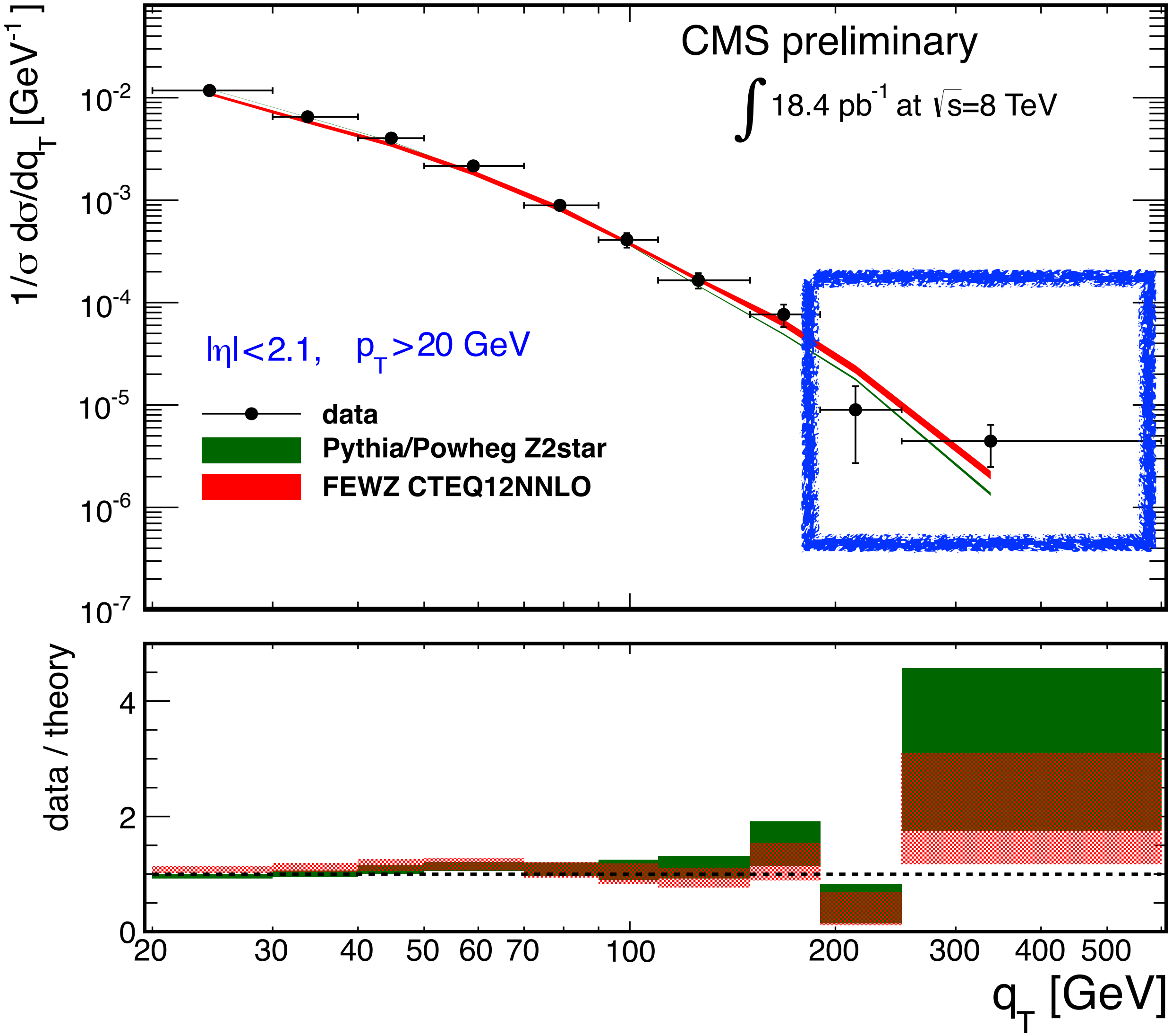


http://cds.cern.ch/record/1525524



Dozens of Z events above 1 TeV!
Statistical precision >1 TeV is ~10%.
So in the Sudakov zone.

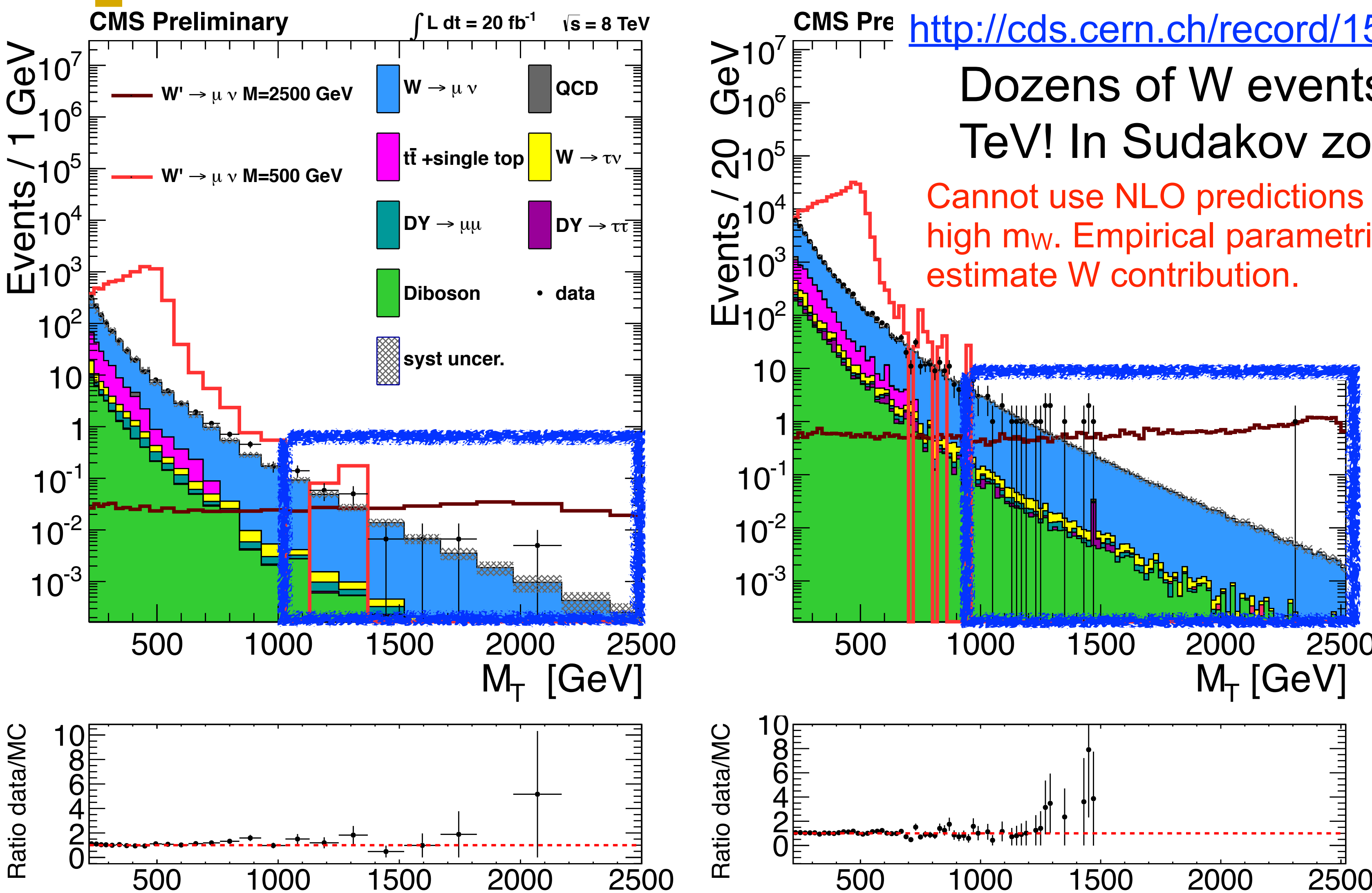
Z p_T distribution in 8 TeV LHC data



https://cdsweb.cern.ch/record/1528579

Expect ~10% negative correction in the last few bins. However, the effect gets diluted due to NLO QCD correction.

Too strong for W? Yes



http://cds.cern.ch/record/1522476

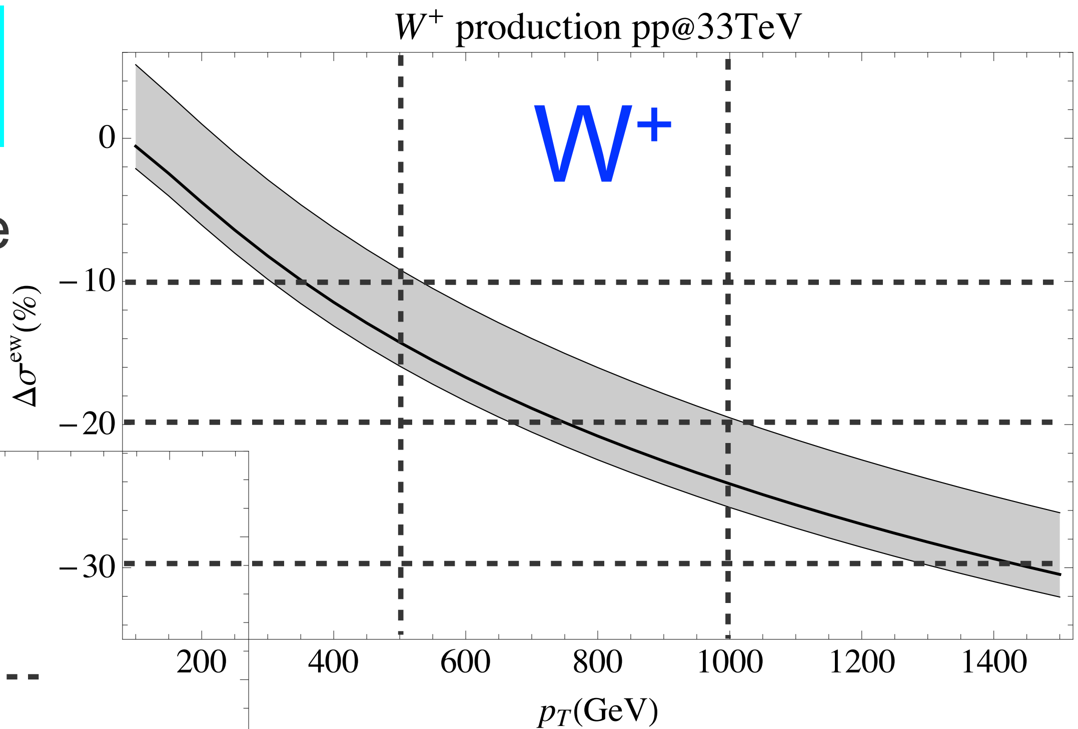
Dozens of W events >1 TeV! In Sudakov zone.

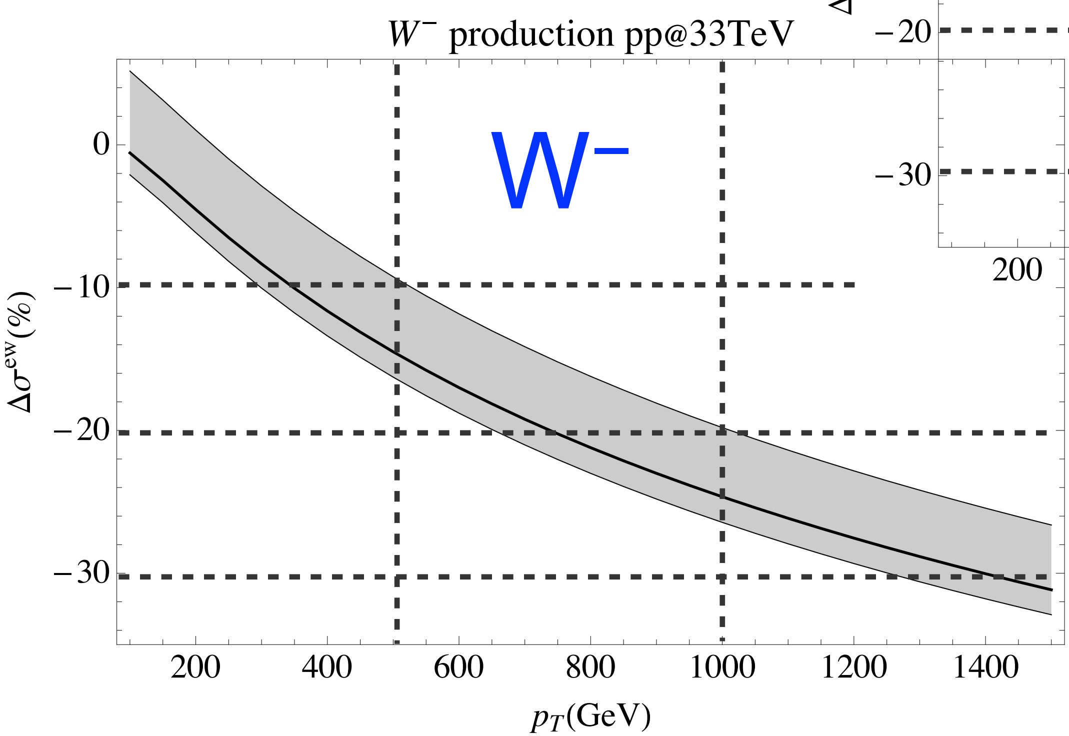
Cannot use NLO predictions blindly at high m_W. Empirical parametrization to estimate W contribution.

Inclusive W^+ and W^- at 33 TeV

Provided by Xavier Garcia Tormo & Thomas Becher

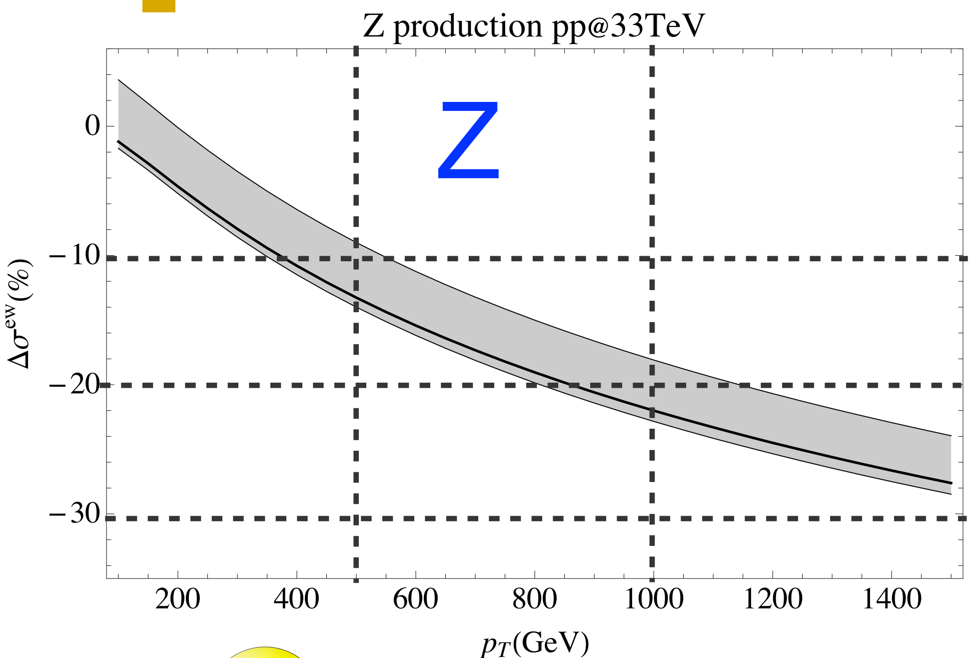
For 8 TeV & 14 TeV results see **arXiv:1305.4202**





- About the same for W^+ & W^-
- Corrections ~ same as in the case of 8 TeV and 14 TeV

Inclusive Z and γ at 33 TeV



Provided by Xavier Garcia Tormo & Thomas Becher

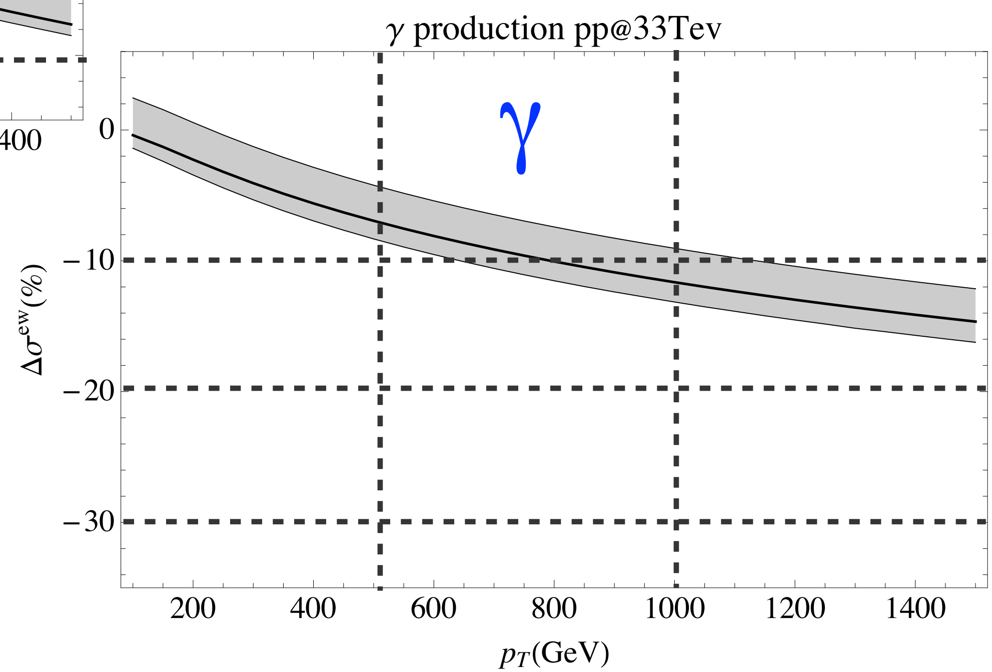
Good

EWK corrections almost independent of the collider energy.

Bad

Getting increasingly more important b/c precision of experimental data & NLO α_S calculation finer than EWK corr.

Coincidental cancellation of worryingly large magnitude.



Z+jets at 33 TeV

as func. of $M_{\ell\ell}$

Provided by Tobias Kasprzik in the format of arXiv:1103.0914

$pp \to l^+l^-$ jet $+ X$ at $\sqrt{s} = 33$ TeV

M_{ll}/ GeV	$100-\infty$	$200-\infty$	$400-\infty$	$1000-\infty$	$2000-\infty$	$4000-\infty$
$\sigma_{\mathrm{Born}}^{\mu=M_Z}$/ pb	19.924(6)	1.6890(2)	0.28005(4)	0.022682(3)	0.0024968(4)	0.00015626(2)
$\sigma_{\mathrm{Born}}^{\mathrm{var}}$/ pb	19.849(6)	1.6482(2)	0.26618(4)	0.020604(3)	0.0021755(3)	0.00012945(2)
$\delta_{\mathrm{EW}}^{\mu=M_Z}$/%	$-9.6(1)$	$-5.74(1)$	$-8.26(1)$	$-14.31(2)$	$-21.69(3)$	$-31.92(4)$
$\delta_{\mathrm{EW}}^{\mathrm{rec},\mu=M_Z}$/%	$-5.3(1)$	$-3.06(1)$	$-5.13(1)$	$-10.11(2)$	$-16.34(3)$	$-24.77(4)$
$\delta_{\mathrm{EW}}^{\mathrm{var}}$/%	$-9.46(8)$	$-5.69(1)$	$-8.14(1)$	$-14.18(2)$	$-21.56(3)$	$-31.88(6)$
$\delta_{\mathrm{EW}}^{\mathrm{rec},\mathrm{var}}$/%	$-5.05(7)$	$-2.94(1)$	$-4.93(1)$	$-9.93(2)$	$-16.14(3)$	$-24.75(6)$
$\delta_{\mathrm{QCD}}^{\mu=M_Z}$/%	29.(1)	14.8(2)	$-0.6(1)$	$-29.5(1)$	$-57.1(1)$	$-89.5(1)$
$\delta_{\mathrm{QCD}}^{\mathrm{var}}$/%	27.9(6)	15.9(2)	2.2(1)	$-23.0(1)$	$-46.6(1)$	$-74.8(1)$
$\delta_{\mathrm{QCD,veto}}^{\mu=M_Z}$/%	5.0(6)	$-8.9(2)$	$-25.5(1)$	$-54.9(1)$	$-82.4(1)$	$-115.3(1)$
$\delta_{\mathrm{QCD,veto}}^{\mathrm{var}}$/%	6.1(4)	$-7.2(2)$	$-20.8(2)$	$-45.8(1)$	$-69.8(1)$	$-98.1(1)$
$\delta_{\gamma,\mathrm{Born}}^{\mu=M_Z}$/%	0.669(1)	2.097(5)	2.409(6)	2.168(6)	1.844(5)	1.610(3)
$\delta_{\gamma,\mathrm{Born}}^{\mathrm{var}}$/%	0.710(1)	2.298(5)	2.721(7)	2.510(7)	2.135(5)	1.822(3)
$\sigma_{\mathrm{full,veto}}^{\mathrm{var}}$/ pb/%	19.32(9)	1.473(4)	0.1965(6)	0.00877(2)	0.000234(3)	$-0.0000365(2)$

Z+jets at 33 TeV as func. of jet p_T

Provided by Tobias Kasprzik

in the format of arXiv:1103.0914

$pp \to l^+l^-$ jet $+ X$ at $\sqrt{s} = 33$ TeV

$p_{T,jet}/$ GeV	$50 - \infty$	$100 - \infty$	$200 - \infty$	$400 - \infty$	$1000 - \infty$	$2000 - \infty$
$\sigma^{\mu=M_Z}_{Born}/$ pb	121.26(1)	33.737(4)	6.3314(7)	0.79429(9)	0.026920(2)	0.0010264(1)
$\sigma^{var}_{Born}/$ pb	120.70(1)	32.654(4)	5.6403(7)	0.60157(6)	0.014491(1)	0.00038663(4)
$\delta^{\mu=M_Z}_{EW}/\%$	−4.68(1)	−5.47(1)	−9.25(1)	−16.15(2)	−29.25(5)	−41.8(2)
$\delta^{rec,\mu=M_Z}_{EW}/\%$	−3.29(3)	−4.48(2)	−8.50(4)	−15.42(3)	−28.59(8)	−41.0(1)
$\delta^{var}_{EW}/\%$	−4.61(1)	−5.31(1)	−8.92(1)	−15.65(2)	−28.48(5)	−40.5(3)
$\delta^{rec,var}_{EW}/\%$	−3.16(3)	−4.42(4)	−8.12(2)	−14.89(2)	−27.62(5)	−39.9(1)
$\delta^{\mu=M_Z}_{QCD}/\%$	56.1(2)	78.7(1)	113.0(1)	160.5(1)	240.4(2)	330.6(3)
$\delta^{var}_{QCD}/\%$	54.0(1)	77.4(1)	117.3(1)	186.0(1)	347.2(2)	609.0(4)
$\delta^{\mu=M_Z}_{QCD,veto}/\%$	13.1(1)	23.3(1)	29.7(1)	27.5(1)	−2.8(1)	−42.2(1)
$\delta^{var}_{QCD,veto}/\%$	12.9(1)	25.6(2)	38.8(1)	49.8(1)	52.6(1)	54.0(1)
$\delta^{\mu=M_Z}_{\gamma,Born}/\%$	0.1377(4)	0.1647(4)	0.1960(5)	0.2442(7)	0.341(1)	0.457(1)
$\delta^{var}_{\gamma,Born}/\%$	0.1489(4)	0.1923(5)	0.2562(7)	0.371(1)	0.661(2)	1.095(3)
$\sigma^{var}_{full,veto}/$ pb/%	130.9(2)	39.36(6)	7.342(9)	0.8091(7)	0.01808(2)	0.000443(1)

See backup slides for prediction as a function of jet p_T

Z+jets at 100 TeV as func. of $M_{\ell\ell}$

Provided by Tobias Kasprzik

in the format of arXiv:1103.0914

$pp \to l^+ l^- \text{ jet} + X$ at $\sqrt{s} = 100$ TeV

M_{ll}/ GeV	$100-\infty$	$200-\infty$	$400-\infty$	$1000-\infty$	$2000-\infty$	$4000-\infty$
$\sigma_{\text{Born}}^{\mu=M_Z}$/ pb	60.70(2)	5.3194(9)	0.9142(1)	0.08462(1)	0.012762(2)	0.0016229(2)
$\sigma_{\text{Born}}^{\text{var}}$/ pb	61.76(2)	5.3548(9)	0.9016(1)	0.07980(1)	0.011500(2)	0.0013850(2)
$\delta_{\text{EW}}^{\mu=M_Z}$/%	$-9.4(1)$	$-5.85(1)$	$-8.41(1)$	$-14.28(2)$	$-21.05(3)$	$-29.97(5)$
$\delta_{\text{EW}}^{\text{rec},\mu=M_Z}$/%	$-5.0(1)$	$-3.23(1)$	$-5.29(1)$	$-10.42(3)$	$-16.42(3)$	$-24.34(5)$
$\delta_{\text{EW}}^{\text{var}}$/%	$-9.5(2)$	$-5.76(1)$	$-8.31(1)$	$-14.08(2)$	$-20.85(3)$	$-29.87(5)$
$\delta_{\text{EW}}^{\text{rec},\text{var}}$/%	$-5.2(2)$	$-3.07(1)$	$-5.15(2)$	$-10.11(2)$	$-16.22(4)$	$-24.09(5)$
$\delta_{\text{QCD}}^{\mu=M_Z}$/%	36.(4)	20.8(3)	7.3(2)	$-18.1(1)$	$-43.3(1)$	$-73.7(1)$
$\delta_{\text{QCD}}^{\text{var}}$/%	29.3(9)	18.4(3)	6.0(1)	$-16.3(1)$	$-37.4(1)$	$-63.3(1)$
$\delta_{\text{QCD,veto}}^{\mu=M_Z}$/%	5.0(9)	$-7.0(2)$	$-21.2(2)$	$-46.8(1)$	$-71.8(1)$	$-102.1(1)$
$\delta_{\text{QCD,veto}}^{\text{var}}$/%	3.8(7)	$-7.4(3)$	$-19.6(2)$	$-41.7(1)$	$-63.1(1)$	$-88.5(2)$
$\delta_{\gamma,\text{Born}}^{\mu=M_Z}$/%	0.532(1)	1.679(4)	2.019(6)	1.988(6)	1.792(6)	1.511(4)
$\delta_{\gamma,\text{Born}}^{\text{var}}$/%	0.568(1)	1.871(4)	2.363(7)	2.464(7)	2.259(7)	1.901(5)
$\sigma_{\text{full,veto}}^{\text{var}}$/ pb/%	58.6(4)	4.75(1)	0.672(1)	0.0373(1)	0.00211(2)	$-0.000228(3)$

Z+jets at 100 TeV as func. of jet p_T

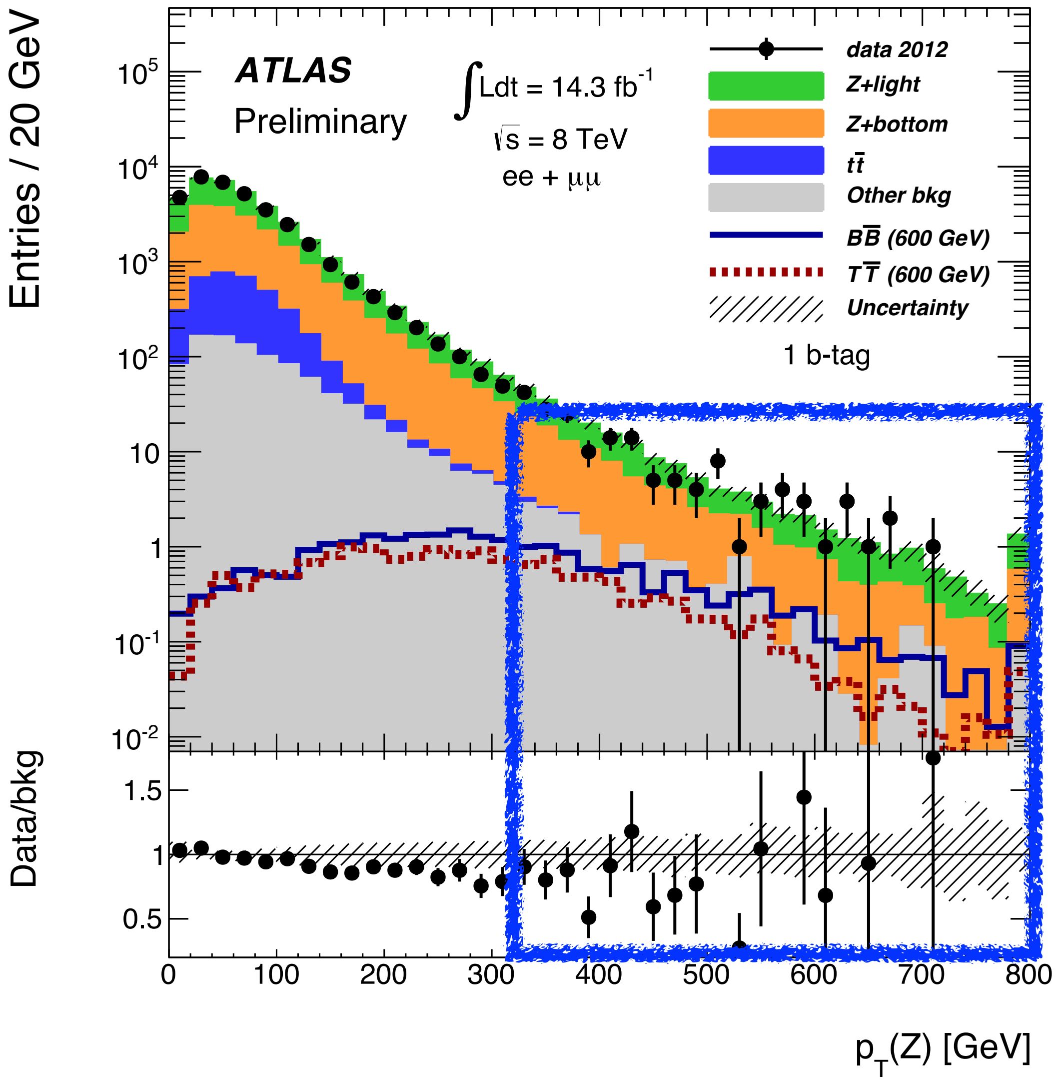
Provided by Tobias Kasprzik
in the format of arXiv:1103.0914

$pp \to l^+l^-$ jet $+ X$ at $\sqrt{s} = 100$ TeV

$p_{T,\text{jet}}$/ GeV	$100-\infty$	$200-\infty$	$400-\infty$	$800-\infty$	$2000-\infty$	$4000-\infty$
$\sigma^{\mu=M_Z}_{\text{Born}}$/ pb	114.29(1)	23.772(3)	3.5452(4)	0.42003(4)	0.017238(1)	0.00094403(9)
$\sigma^{\text{var}}_{\text{Born}}$/ pb	118.30(1)	23.762(3)	3.1922(3)	0.31583(3)	0.0091290(9)	0.00035205(3)
$\delta^{\mu=M_Z}_{\text{EW}}$/%	−5.62(1)	−9.57(1)	−16.86(2)	−27.11(8)	−43.5(1)	−58.8(1)
$\delta^{\text{rec},\mu=M_Z}_{\text{EW}}$/%	−4.65(3)	−8.72(2)	−16.08(2)	−26.29(4)	−43.15(7)	−58.5(2)
$\delta^{\text{var}}_{\text{EW}}$/%	−5.50(1)	−9.29(1)	−16.38(3)	−26.36(4)	−43.2(2)	−57.5(1)
$\delta^{\text{rec},\text{var}}_{\text{EW}}$/%	−4.48(2)	−8.52(2)	−15.62(2)	−25.64(4)	−42.21(7)	−56.8(1)
$\delta^{\mu=M_Z}_{\text{QCD}}$/%	97.4(2)	146.0(1)	215.2(2)	288.7(2)	378.0(3)	472.6(5)
$\delta^{\text{var}}_{\text{QCD}}$/%	85.4(2)	130.0(2)	201.7(1)	298.8(2)	487.9(3)	769.0(7)
$\delta^{\mu=M_Z}_{\text{QCD,veto}}$/%	35.7(2)	54.2(1)	66.7(1)	61.3(1)	13.2(2)	−43.1(1)
$\delta^{\text{var}}_{\text{QCD,veto}}$/%	29.6(2)	47.4(1)	65.5(1)	76.4(3)	65.6(2)	51.5(1)
$\delta^{\mu=M_Z}_{\gamma,\text{Born}}$/%	0.1218(3)	0.1400(4)	0.1681(5)	0.2114(7)	0.291(1)	0.382(1)
$\delta^{\text{var}}_{\gamma,\text{Born}}$/%	0.1407(3)	0.1799(5)	0.2482(7)	0.365(1)	0.630(2)	1.006(5)
$\sigma^{\text{var}}_{\text{full,veto}}$/ pb/%	147.0(2)	32.86(4)	4.767(4)	0.475(1)	0.01124(2)	0.0003343(7)

See backup slides for prediction as a function of jet p_T

Distribution in 8 TeV LHC data



ATLAS analysis of Z+jets data with one b-tagged jet

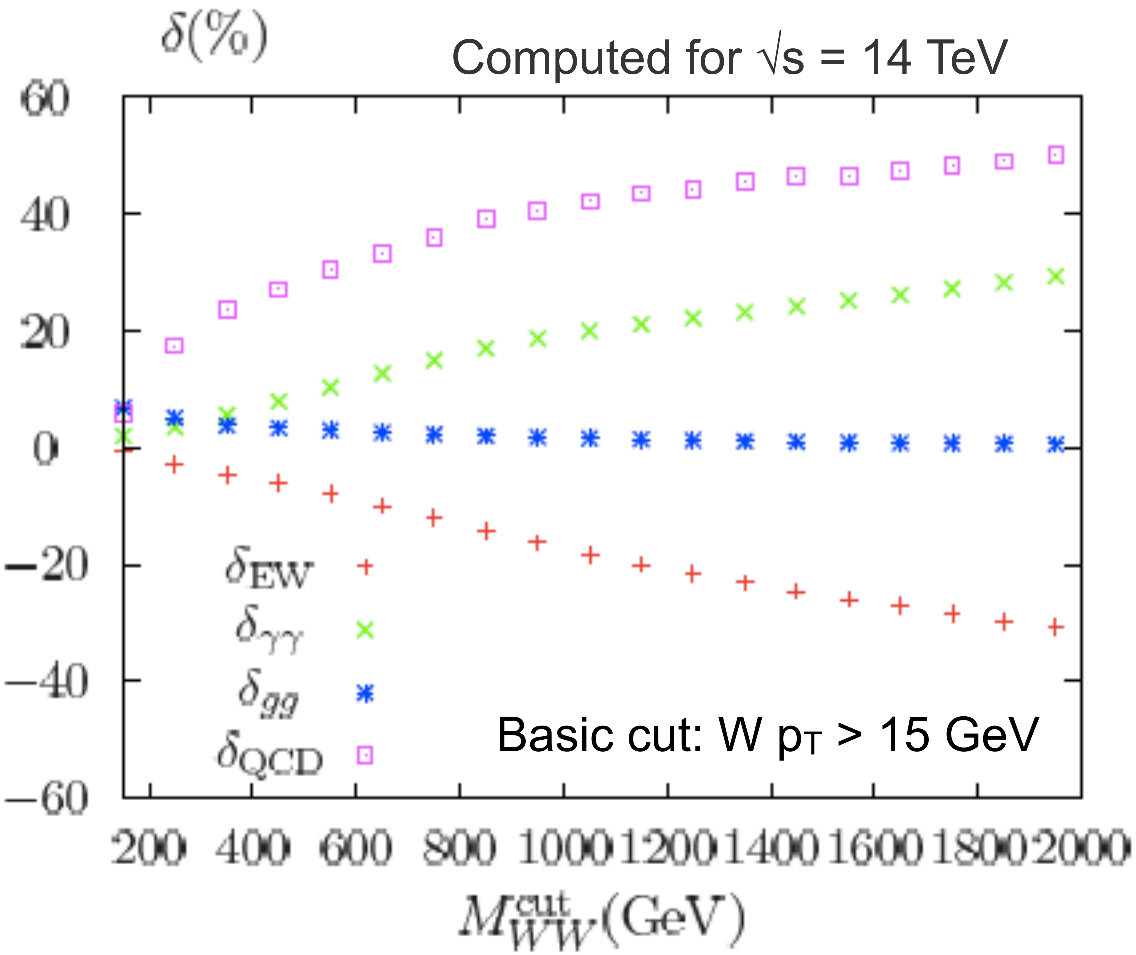
http://cds.cern.ch/record/1557773

In Sudakov zone

Additional experimental plot in backup

WW production: a curious case

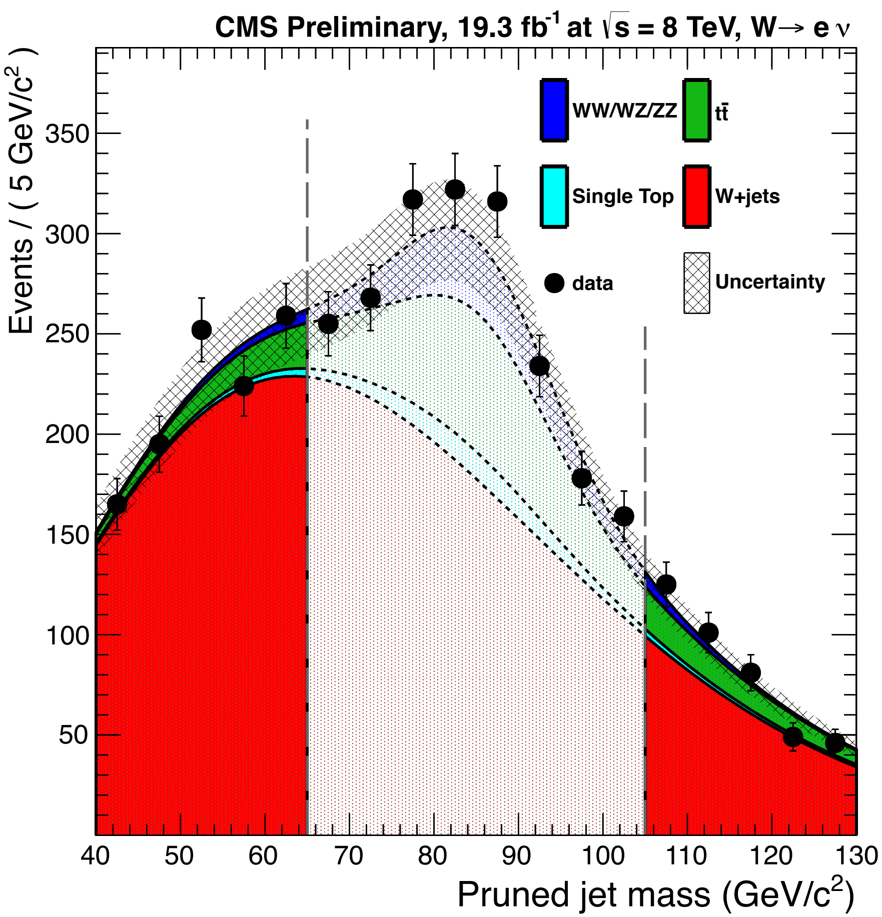
See talk by T. Kasprzik at ICHEP 2012

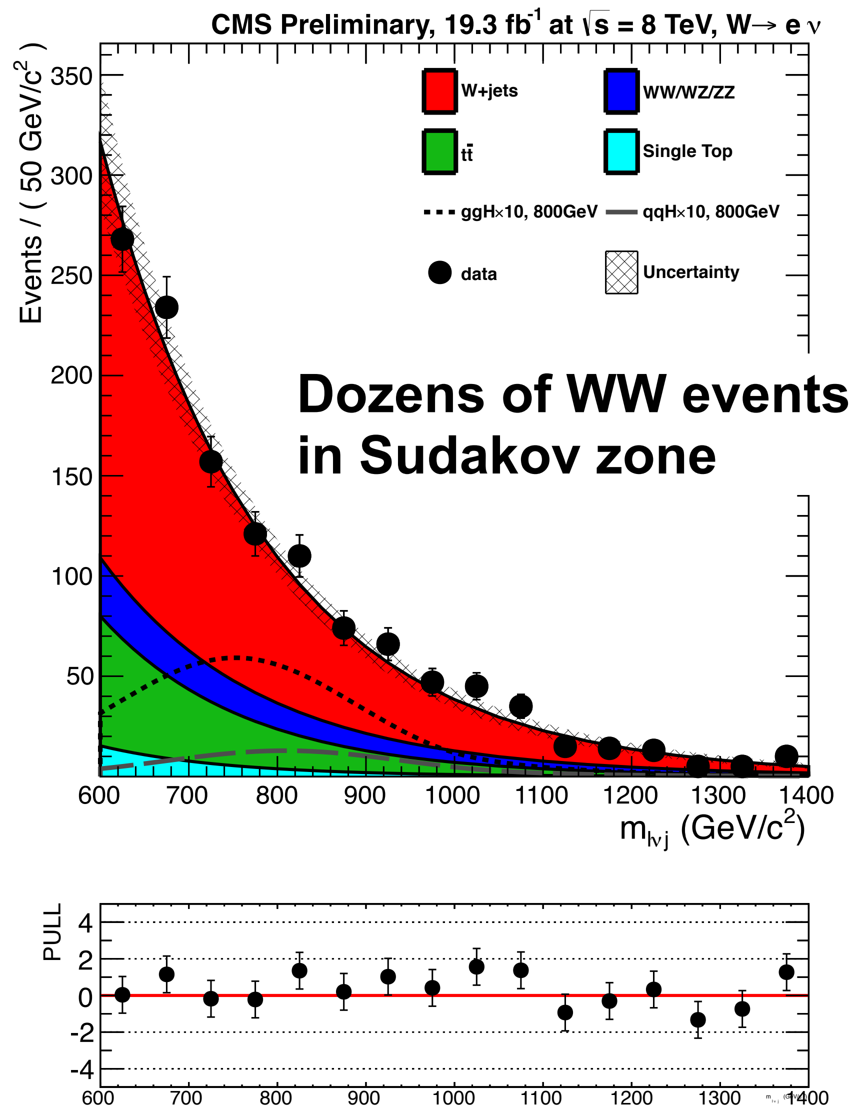


EWK and QCD corrections partially cancel out, resulting in net positive enhancement at high WW invariant mass

Again, coincidental cancellation of worryingly large magnitude.

Too strong for VV? Yes, in some cases.



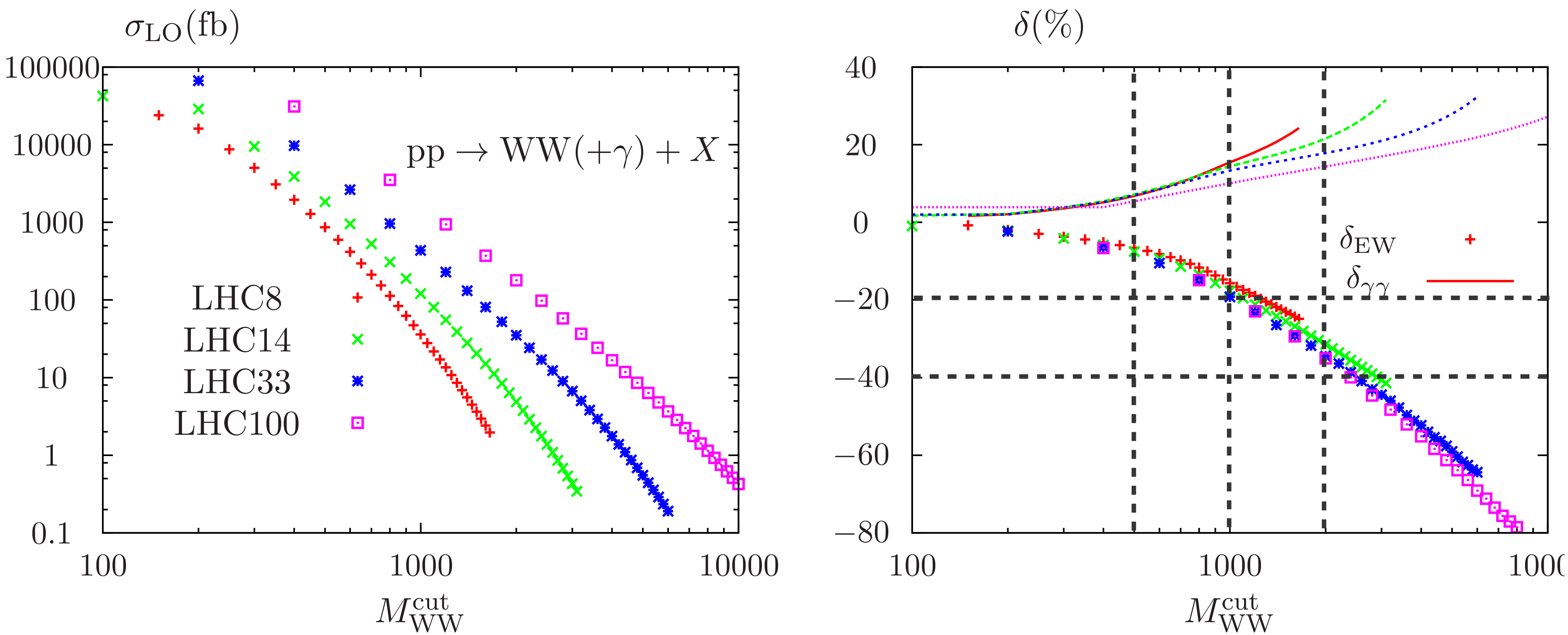


Dozens of WW events in Sudakov zone

Additional experimental plot in backup

WW at 33 TeV and 100 TeV

Provided by Tobias Kasprzik

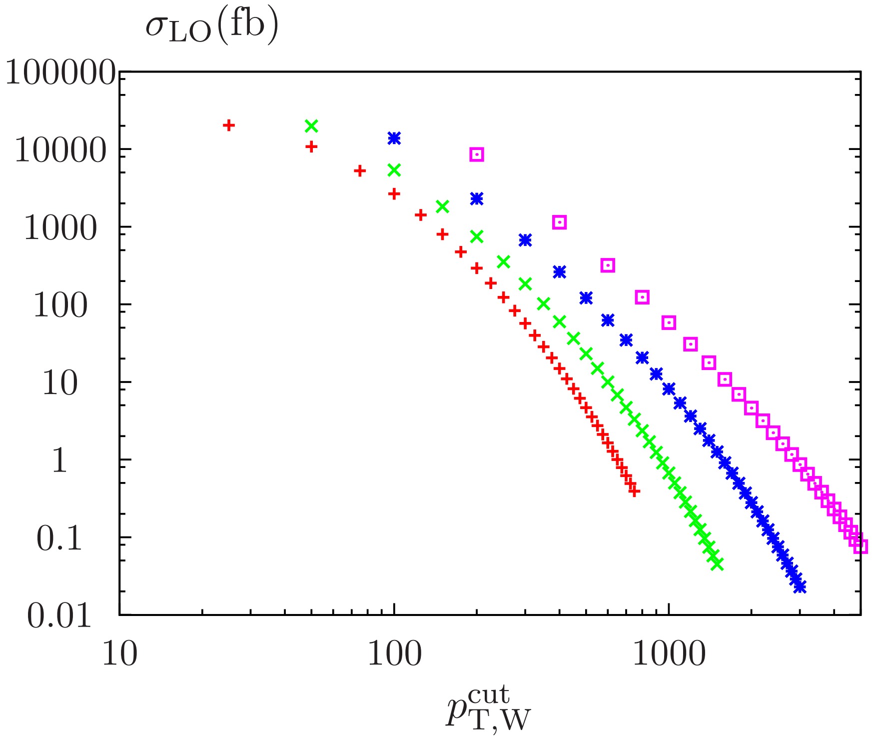


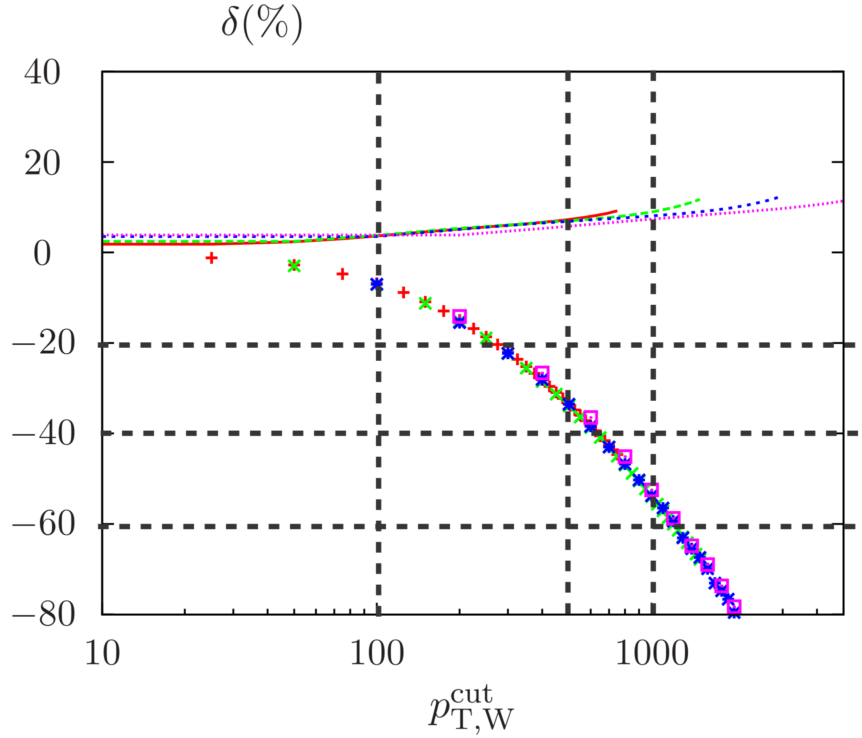
The EWK corrections by themselves do not depend much on the collider energy, but γγ→WW increases at a much slower rate at high collider energies. So, the sum of the two is more −ve. Need to watch out for NLO QCD correction to understand the net cancellation effect.

WW at 33 TeV and 100 TeV

Provided by Tobias Kasprzik

Also computed as a function of $p_{T,W}$ cut





Summary: Quick recap of Sudakov zone survey

Are we in the Sudakov zone ?

Process	Now	14 TeV	33/100 TeV
Inclusive jet, dijet	Yes	Yes	Yes
Inclusive W/Z tail	Yes	Yes	Yes
$V\gamma$ ($\ell\ell\gamma$, $\ell\nu\gamma$) tail	No	Yes	Yes
V+jets tail	Yes	Yes	Yes
WW leptonic	Close	Yes	Yes
WZ,ZZ leptonic	No	No	Yes
VV semi-leptonic	Yes	Yes	Yes

Previous report and additional survey of 7 TeV LHC data at:
http://conference.ippp.dur.ac.uk/conferenceDisplay.py?confId=331

Summary

☑ The size of EWK corrections for many processes at LHC are approaching the current precision of the measurement

- Important at high mass/p_T tails

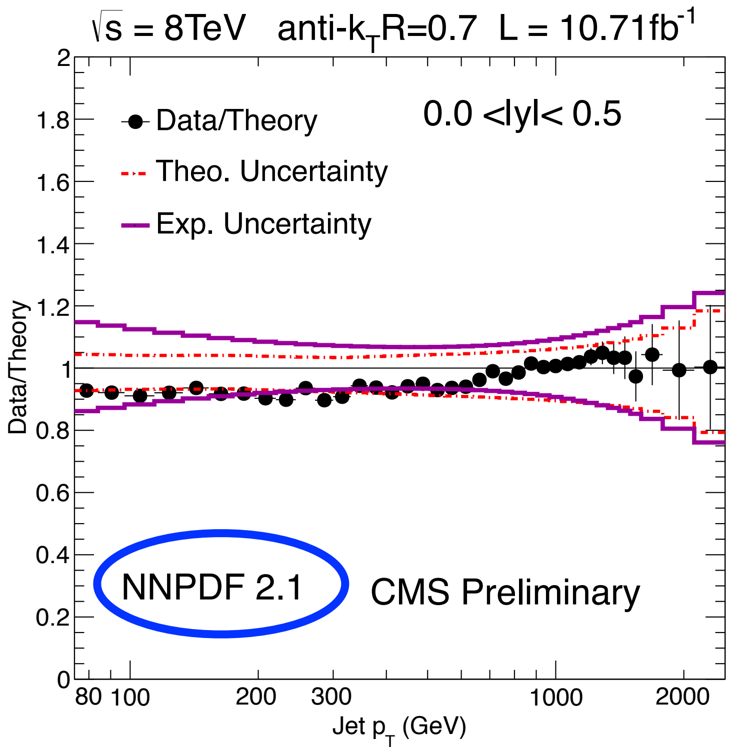
☑ Extrapolations made using current LHC data and dedicated calculations for 33 TeV & 100 TeV collider energies suggest that

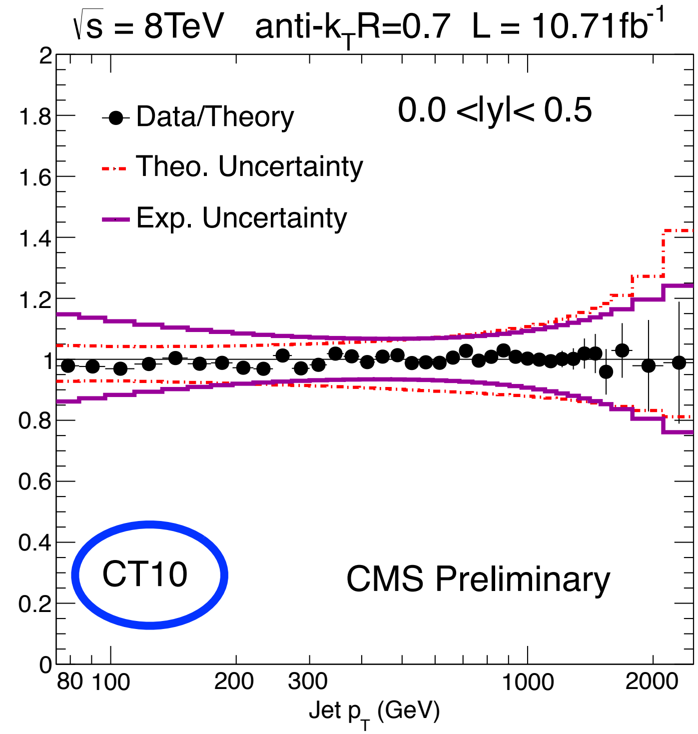
- Corrections are large in kin regime accessible at higher energies
- Important for almost all abundant (background) processes
- Do not change dramatically with collider energy

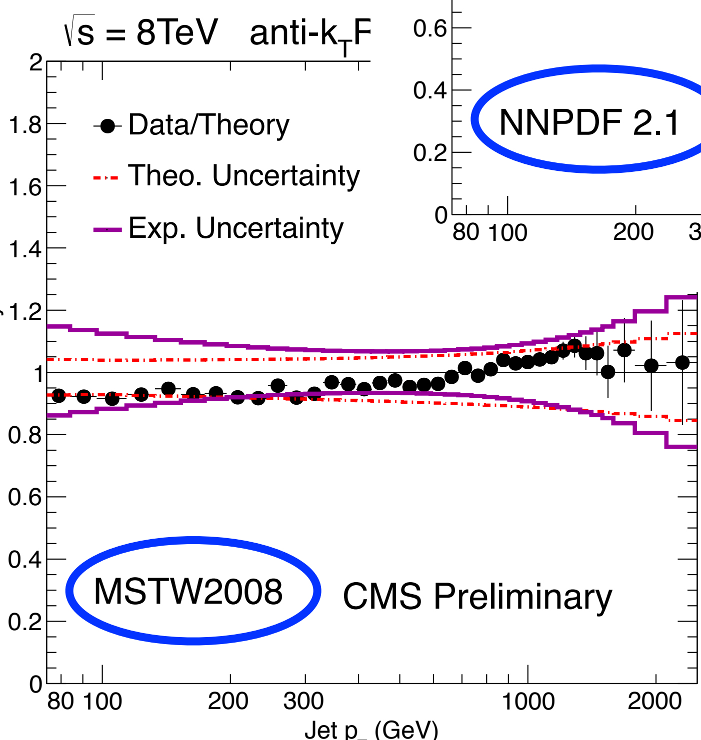
Plan to write up this report & include in the Snowmass white paper

BACKUP SLIDES

Aside: PDF dependence of QCD (α_S) uncertainty



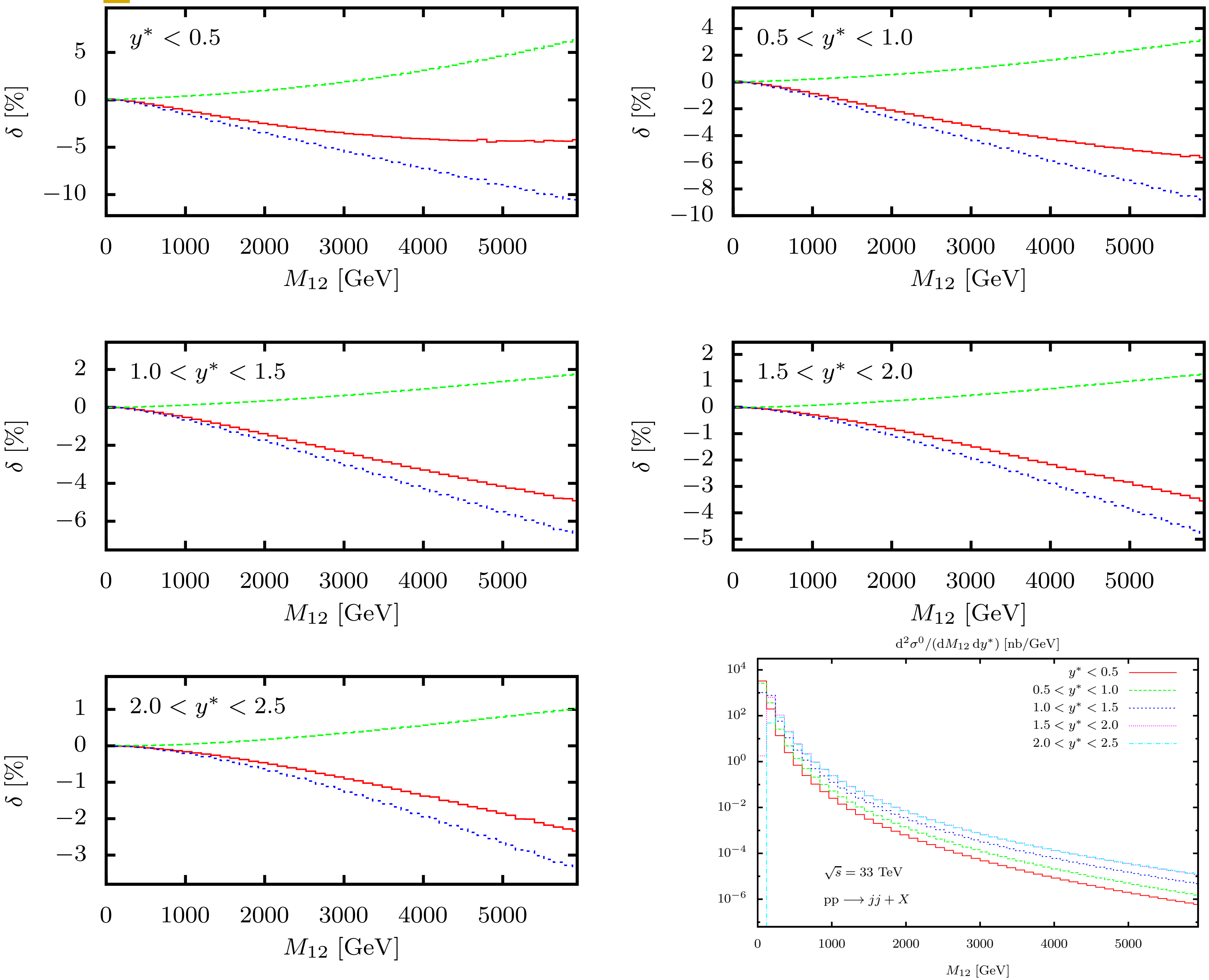




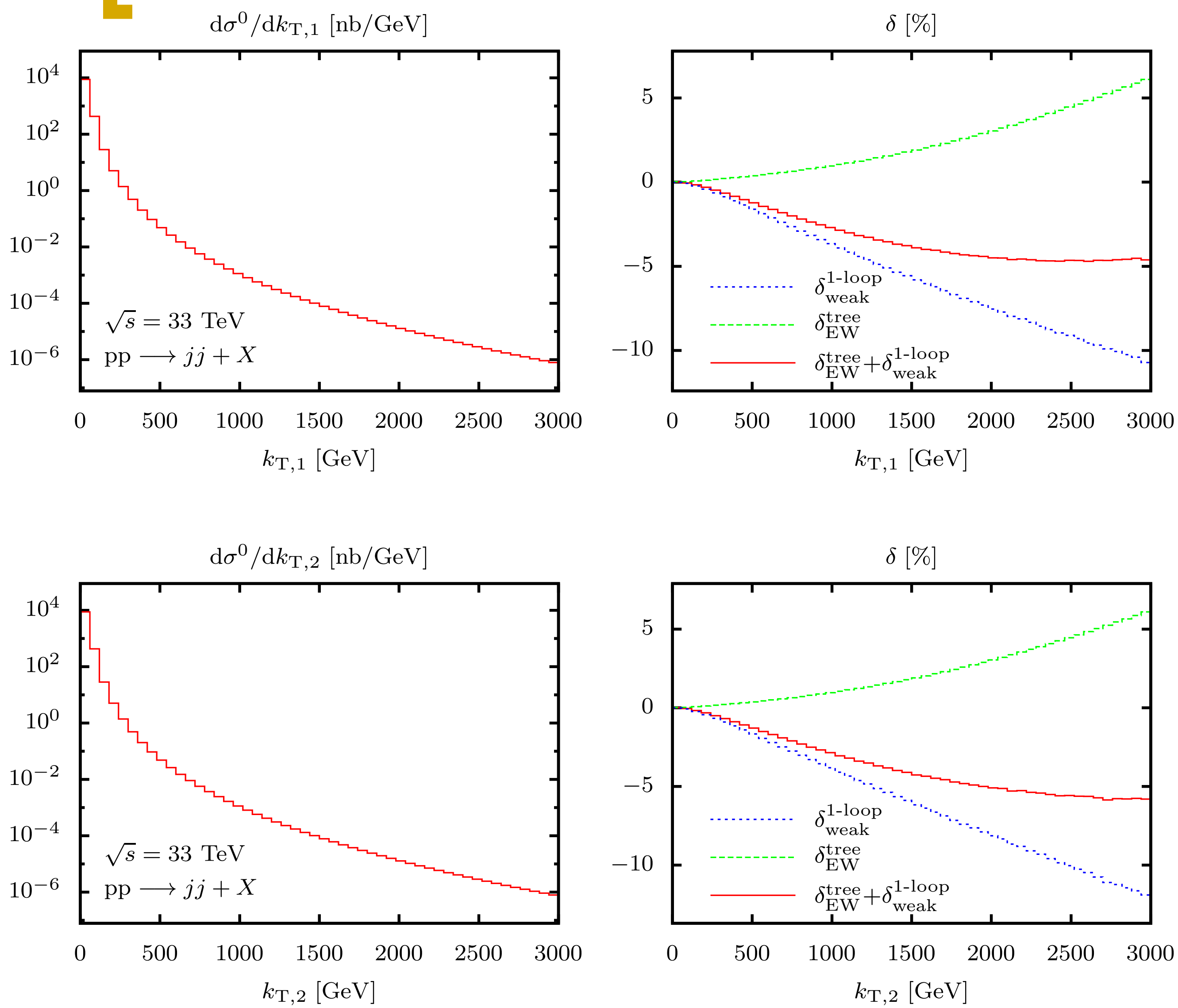
For more plots (other rapidity bins) see

https://cdsweb.cern.ch/record/1547589

Dijet @33 TeV: Dissecting into rapidity regions



Dijet @33 TeV: differential in jet p_T



Z+jets at 33 TeV: as a function of lepton p_T

$\mathrm{pp} \to l^+l^-\ \mathrm{jet} + X$ at $\sqrt{s} = 33\,\mathrm{TeV}$

p_{T,l^+} / GeV	$50-\infty$	$100-\infty$	$200-\infty$	$400-\infty$	$1000-\infty$	$2000-\infty$
$\sigma^{\mu=M_Z}_{\mathrm{Born}}$ / pb	138.38(2)	12.641(2)	1.7316(3)	0.19986(3)	0.006439(1)	0.00023702(5)
$\sigma^{\mathrm{var}}_{\mathrm{Born}}$ / pb	138.01(2)	12.011(2)	1.4856(2)	0.14747(2)	0.0037329(7)	0.00011702(2)
$\delta^{\mu=M_Z}_{\mathrm{EW}}$ /%	−6.99(1)	−9.26(2)	−13.57(7)	−19.96(7)	−31.0(2)	−37.1(3)
$\delta^{\mathrm{rec},\mu=M_Z}_{\mathrm{EW}}$ /%	−3.97(9)	−6.11(4)	−10.14(5)	−16.12(9)	−25.8(2)	−31.7(2)
$\delta^{\mathrm{var}}_{\mathrm{EW}}$ /%	−7.00(1)	−9.08(2)	−13.18(3)	−19.11(6)	−26.7(3)	−31.(2)
$\delta^{\mathrm{rec},\mathrm{var}}_{\mathrm{EW}}$ /%	−4.12(8)	−5.82(5)	−9.65(4)	−15.07(7)	−21.8(3)	−23.3(7)
$\delta^{\mu=M_Z}_{\mathrm{QCD}}$ /%	32.3(2)	56.3(2)	49.6(2)	28.4(3)	−21.4(2)	−67.9(3)
$\delta^{\mathrm{var}}_{\mathrm{QCD}}$ /%	30.5(2)	53.2(2)	51.7(2)	42.0(2)	15.9(2)	−15.1(7)
$\delta^{\mu=M_Z}_{\mathrm{QCD,veto}}$ /%	7.9(2)	22.5(3)	17.3(1)	−1.9(2)	−46.4(2)	−89.9(3)
$\delta^{\mathrm{var}}_{\mathrm{QCD,veto}}$ /%	7.7(2)	23.4(2)	25.5(3)	19.8(1)	$-1.(1)\times 10^{1}$	−35.4(6)
$\delta^{\mu=M_Z}_{\gamma,\mathrm{Born}}$ /%	0.1204(3)	0.3068(8)	0.426(1)	0.525(1)	0.683(3)	0.817(3)
$\delta^{\mathrm{var}}_{\gamma,\mathrm{Born}}$ /%	0.1284(4)	0.355(1)	0.559(1)	0.792(2)	1.200(4)	1.498(7)
$\sigma^{\mathrm{var}}_{\mathrm{full,veto}}$ / pb/%	139.2(3)	13.78(2)	1.677(4)	0.1497(3)	0.0025(7)	0.000041(2)

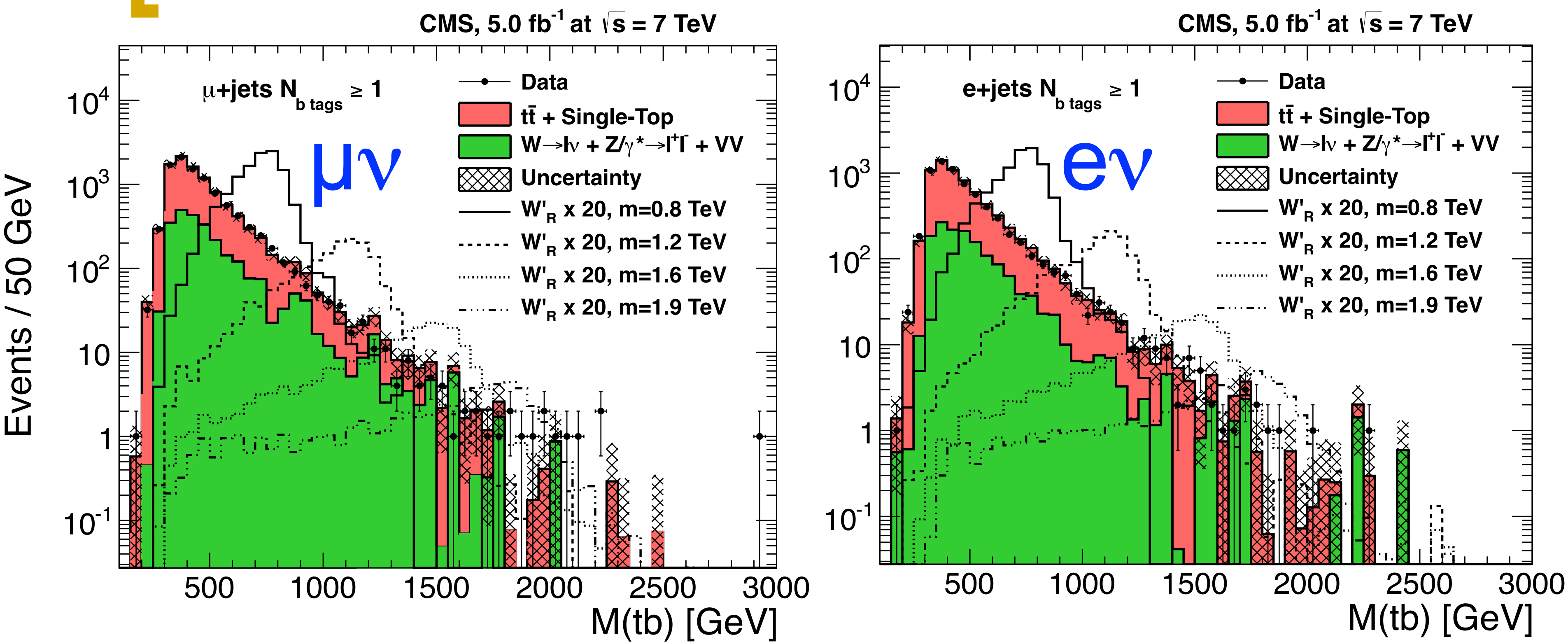
Z+jets at 100 TeV: as a function of lepton p_T

$pp \to l^+l^-$ jet $+ X$ at $\sqrt{s} = 100$ TeV

p_{T,l^+} / GeV	$100-\infty$	$200-\infty$	$400-\infty$	$800-\infty$	$2000-\infty$	$4000-\infty$
$\sigma_{\rm Born}^{\mu=M_Z}$ / pb	44.075(8)	6.865(1)	0.9684(1)	0.11379(2)	0.0045639(8)	0.00024532(5)
$\sigma_{\rm Born}^{\rm var}$ / pb	45.107(9)	6.643(1)	0.8362(1)	0.08329(1)	0.0025868(5)	0.00011752(3)
$\delta_{\rm EW}^{\mu=M_Z}$ /%	$-9.68(2)$	$-14.56(3)$	$-22.5(3)$	$-31.1(1)$	$-44.5(3)$	$-51.8(8)$
$\delta_{\rm EW}^{\rm rec,\mu=M_Z}$ /%	$-6.53(5)$	$-11.17(4)$	$-18.17(6)$	$-26.8(1)$	$-39.8(2)$	$-49.(1)$
$\delta_{\rm EW}^{\rm var}$ /%	$-9.54(2)$	$-14.22(3)$	$-21.20(6)$	$-29.6(2)$	$-41.8(8)$	$-41.8(6)$
$\delta_{\rm EW}^{\rm rec,var}$ /%	$-6.32(6)$	$-10.81(4)$	$-17.38(6)$	$-25.1(1)$	$-39.(1)$	$-35.4(8)$
$\delta_{\rm QCD}^{\mu=M_Z}$ /%	73.6(3)	77.4(2)	68.2(2)	41.1(2)	$-20.5(6)$	$-75.2(8)$
$\delta_{\rm QCD}^{\rm var}$ /%	60.1(4)	62.5(2)	58.2(2)	44.9(2)	12.(2)	$-24.4(4)$
$\delta_{\rm QCD,veto}^{\mu=M_Z}$ /%	34.7(2)	40.5(2)	33.4(2)	10.0(3)	$-49.1(4)$	$-99.6(4)$
$\delta_{\rm QCD,veto}^{\rm var}$ /%	26.9(2)	33.2(4)	32.7(1)	23.4(3)	$-7.5(3)$	$-45.1(4)$
$\delta_{\gamma,\rm Born}^{\mu=M_Z}$ /%	0.2264(7)	0.3036(9)	0.368(1)	0.441(1)	0.564(3)	0.667(3)
$\delta_{\gamma,\rm Born}^{\rm var}$ /%	0.2562(7)	0.385(1)	0.538(1)	0.743(3)	1.093(5)	1.32(1)
$\delta_{\gamma,\rm NLO}^{\mu=M_Z}$ /%	0.2264(7)	0.3036(9)	0.368(1)	0.441(1)	0.564(3)	0.667(3)
$\delta_{\gamma,\rm NLO}^{\rm var}$ /%	0.2562(7)	0.385(1)	0.538(1)	0.743(3)	1.093(5)	1.32(1)
$\sigma_{\rm full,veto}^{\rm var}$ / pb/%	53.1(1)	7.93(2)	0.937(1)	0.0788(3)	0.00134(2)	0.0000169(9)

W+jets with at least 1 b-tag

arXiv:1208.0956



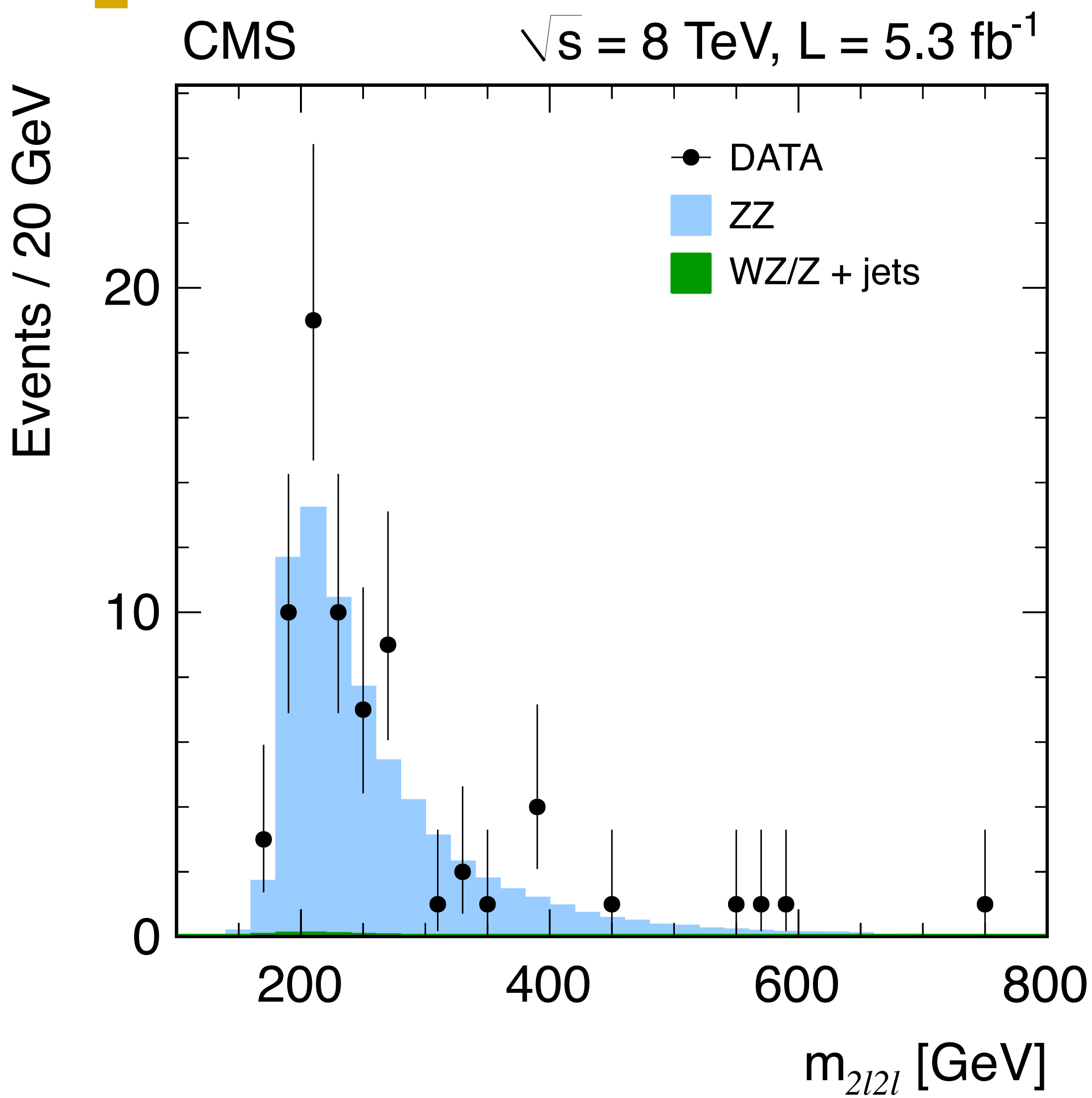
Dozens of events above 1 TeV

Already in Sudakov zone!

- Better than 5% precision expected in 8 TeV data

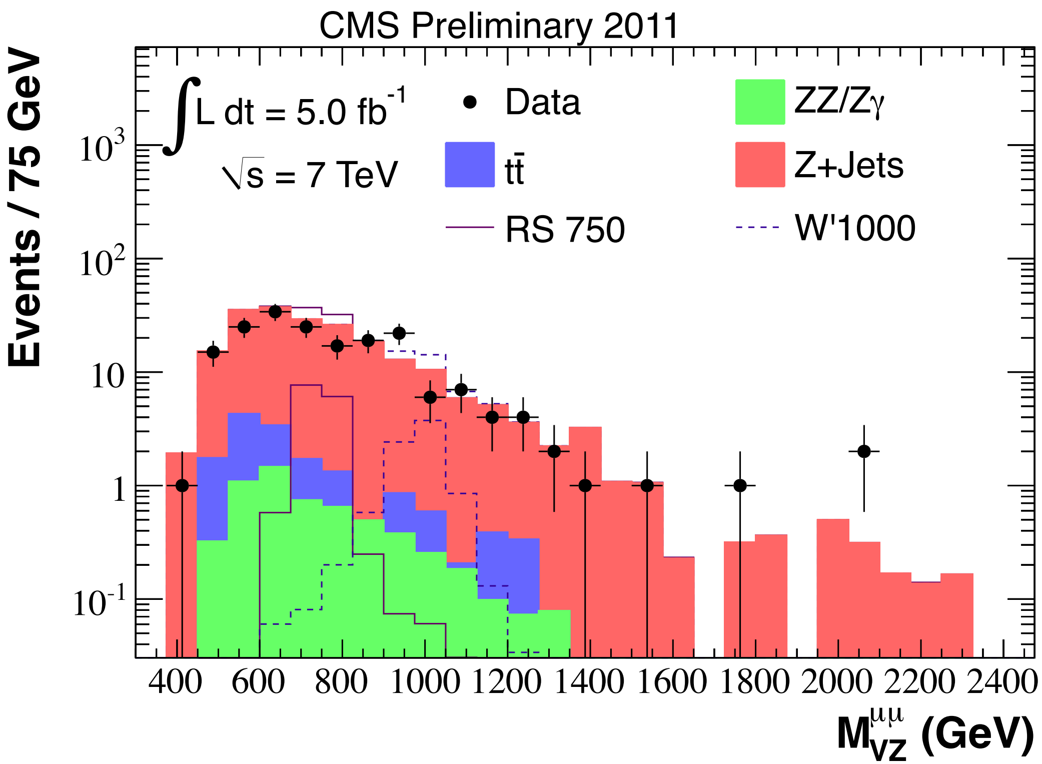
Validate W+jets shape using data: compare 0 b-tagged sample in data with W+jets MC; take difference as systematics.

ZZ (leptonic) invariant mass in 8 TeV data



Diboson at 7 TeV: WZ/ZZ→ℓℓ+j (boosted)

http://cdsweb.cern.ch/record/1444879



- ✦The other boson (W or Z) decays hadronically into a single (merged) jet
  - -anti-kT 0.7 jet
  - -highly boosted: $p_T > 250$ GeV
- ✦Plot invariant mass of the VZ system.

A dozen events beyond 1 TeV. Will be in the Sudakov zone in 2012.

Fit the smoothly falling spectrum to set limit.