New physics?

Bulk

SEARCH 2016

Matt Strassler (Harvard)

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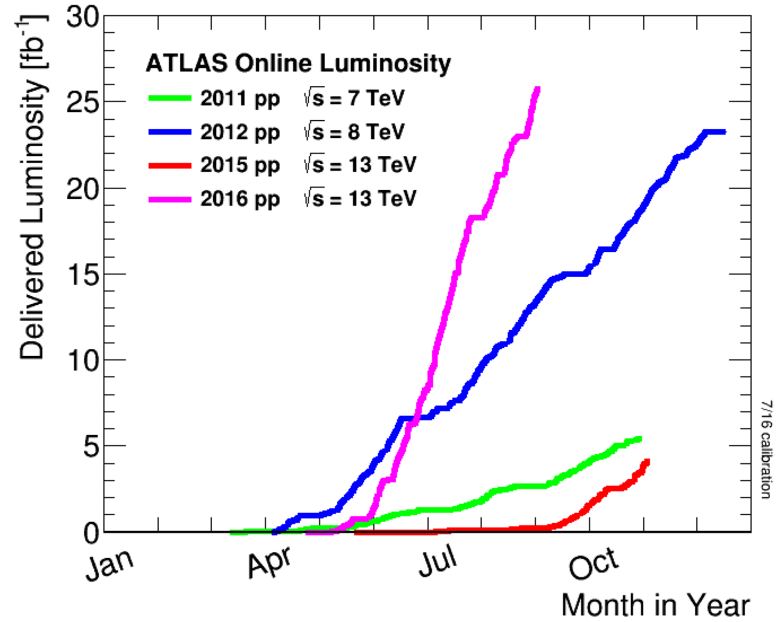
Slow-Growth Era of LHC

- Statistical improvements will be slow,

  starting soon… well, now…



How to make rapid progress?

- Unconventional searches
    - *David Curtin's talk*
  - If it's never been done before… (or not since 2011)… who knows?

- Precision (or "high sensitivity")
  - Reducing theoretical & systematic uncertainties on existing searches
  - Planning new searches that weren't previously worth doing

Bulk of a Distribution?

Here:

- Project full space of final states onto a variable or two
- Don’t just look on the tail for deviations from prediction

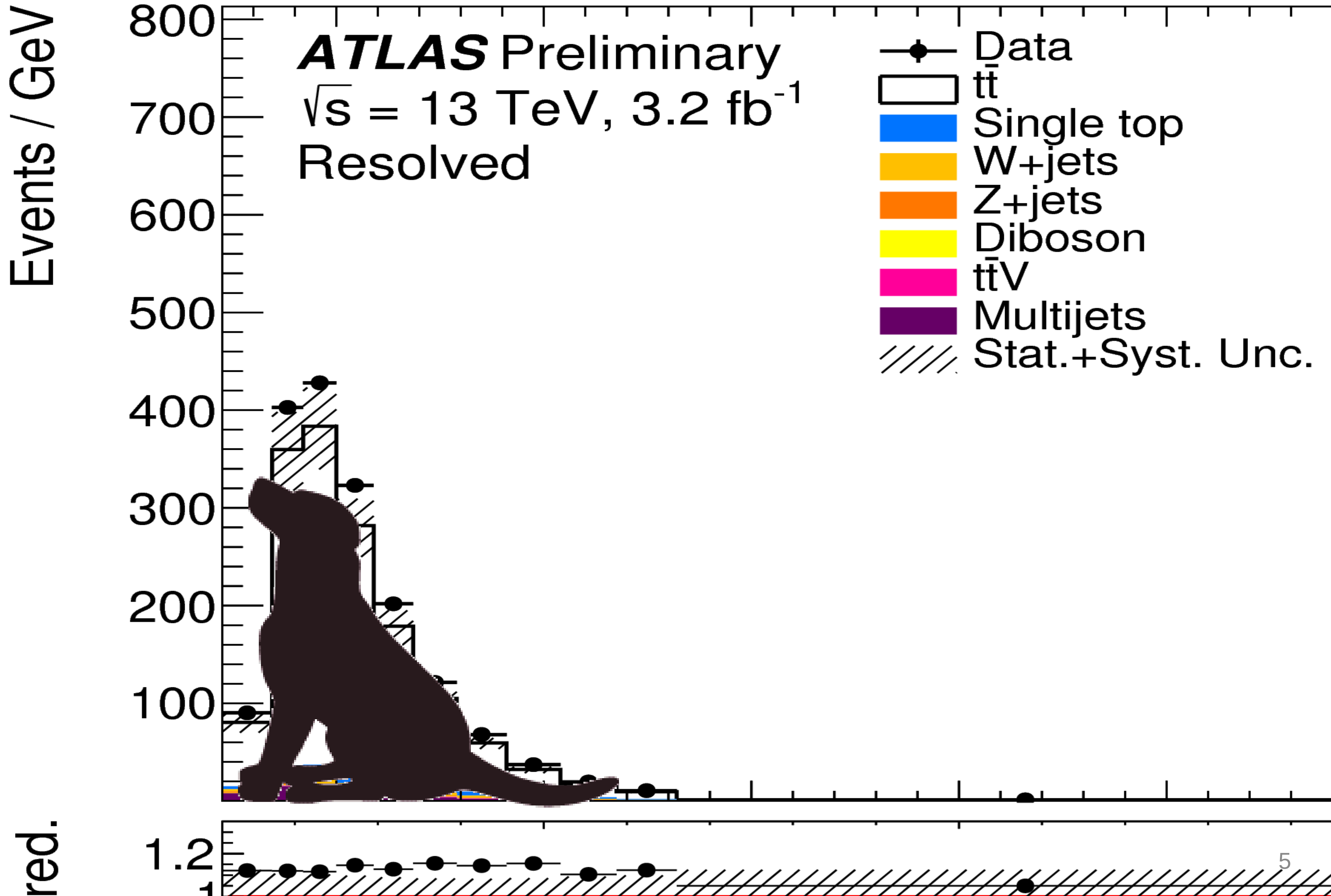
Reasons:

- While there has been a lot of focus for searches on
  - High mass
  - High p_T
  - High MET

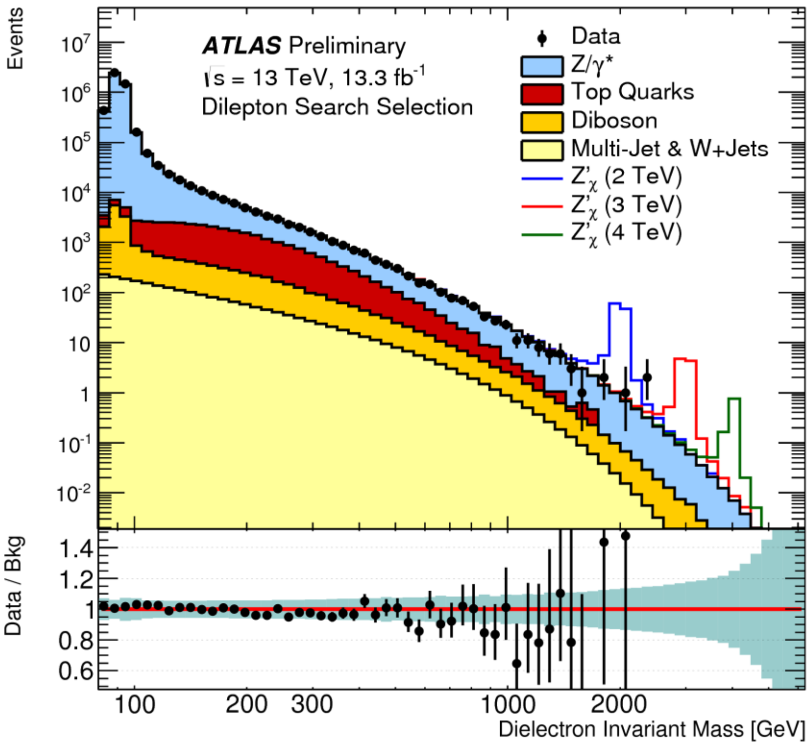
  of course many phenomena can show up lower in the plot

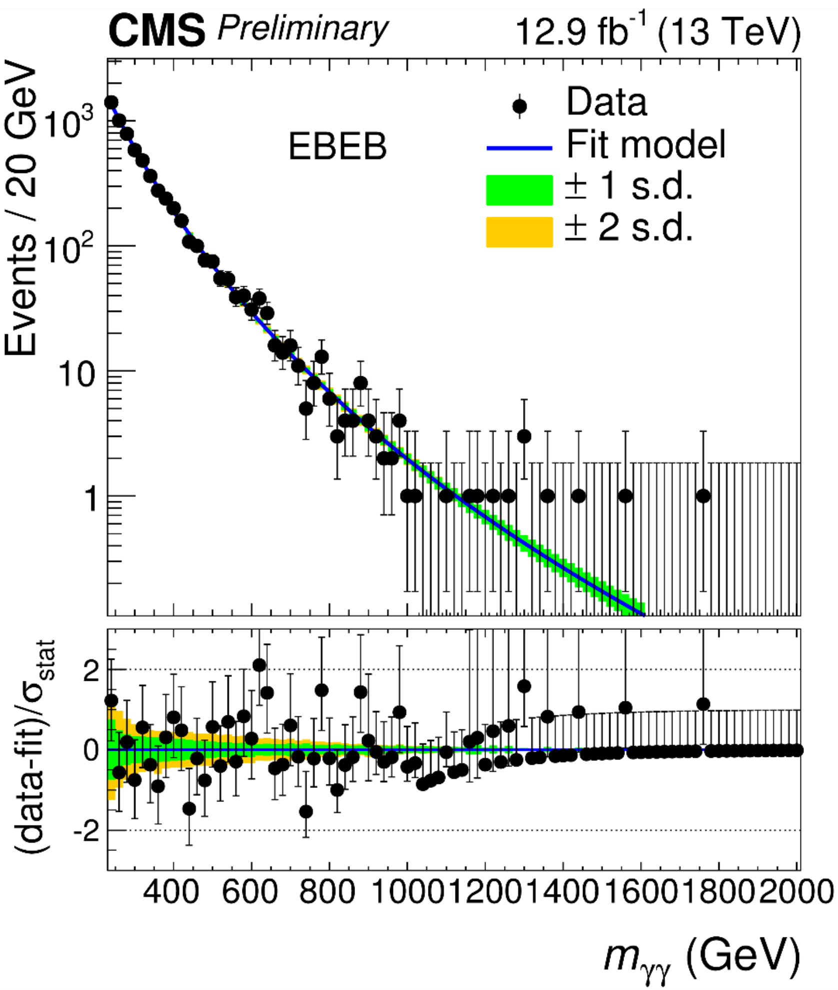
- Especially true now as limits on heavy particles begin to max out
  - Precision era means access to EW production, other rare processes
  - SM precision tests (needed for later BSM) demand high statistics

Don’t Let the Tail Wag the Dog



Inclusive is not Conclusive



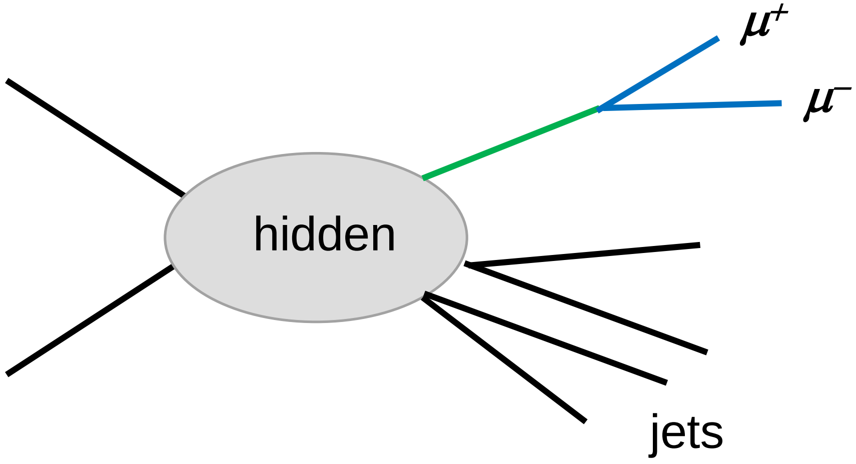


Physics Hidden in Inclusive Distributions

In various models *(common in hidden valleys/dark sectors)*

MJS & Zurek '06
Han,Si,Zurek & MJS '07

- Rare or unusual production of new neutral particle
- Bump, edge, endpoint, dip, wiggle is present
  - but swamped in inclusive background



Rare, prompt, light dilepton resonance along with hard jets

This happens in the SM too

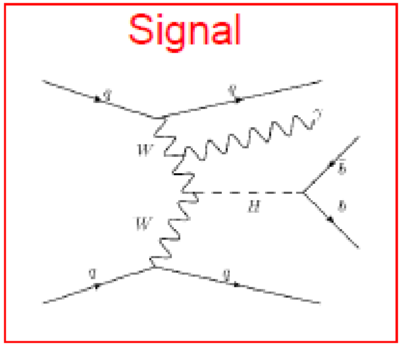
Higgs to bb can't be seen inclusively either

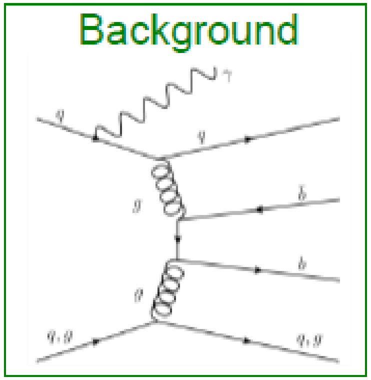
- So do a semi-exclusive search… cut background much more than signal
  - VH (require MET/lepton, maybe mild boost)
  - Or… from Guillemin talk

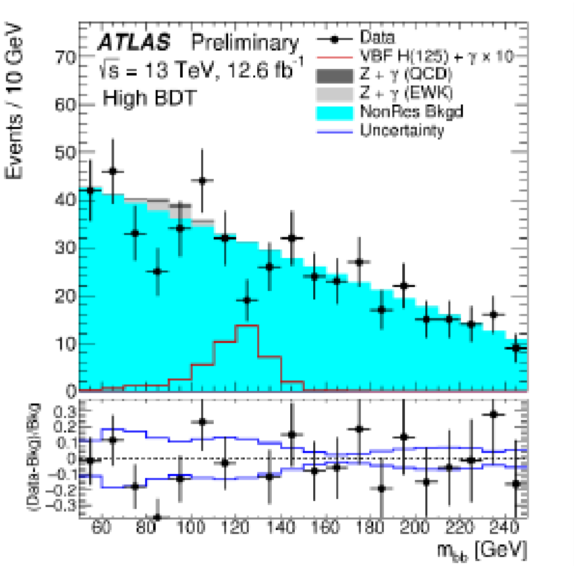
ATLAS-CONF-2016-063

Analysis key points

- $H \to bb$ VBF analysis (not in association with a photon) performed in Run 1 (sensitivity ~5 times the SM)
- Topological 4-jet+γ trigger signature implemented at Level-1 for Run 2
- Gluon-induced component of the dominant non-resonant bbjjγ suppressed
- BDT against the non-resonant background: m_{bb} fits in 3 BDT regions







Physics Hidden in Inclusive Distributions

In various models *(common in hidden valleys/dark sectors)*

- Rare or unusual production of new neutral particle
- Bump, edge, endpoint, dip, wiggle is present
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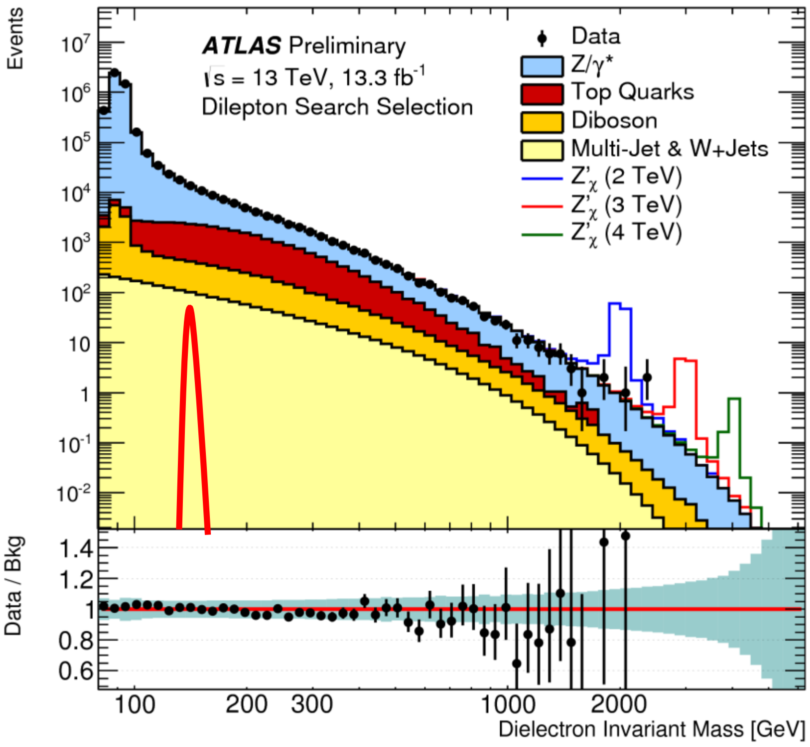
- Point:
  - Higgs → bb resonance is invisible in inclusive production
  - But a semi-exclusive search can reveal it
    - The selection criterion reduces background, keeps signal

- We should do this for other resonance searches as a matter of course!

Inclusive is not Conclusive

Inclusive



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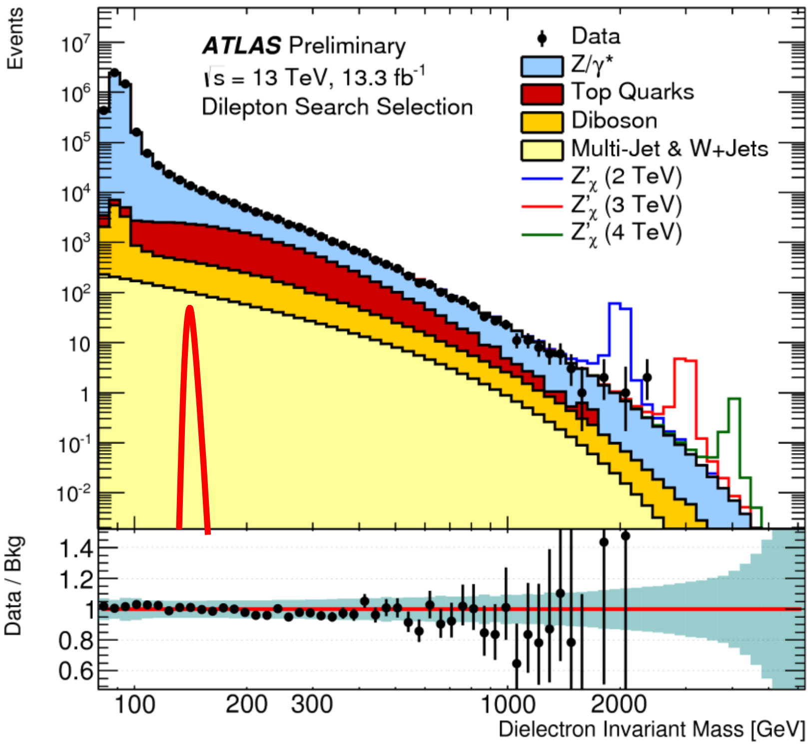
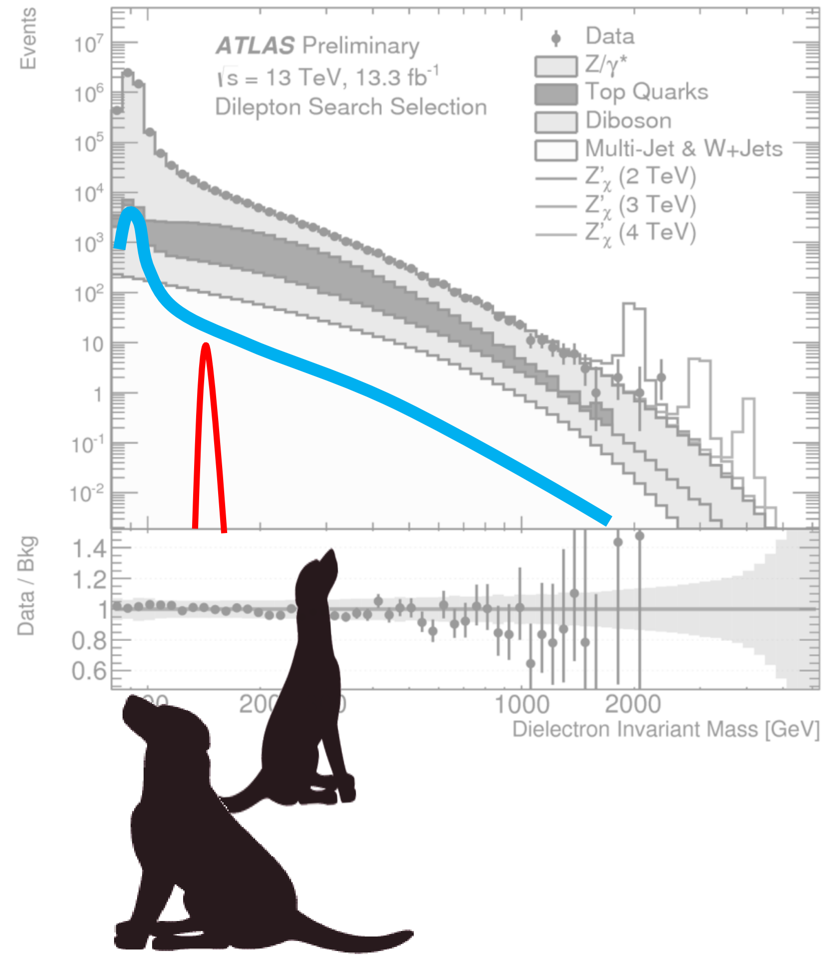
Inclusive



Require 4 jets and high HT and… presto!



Physics Hidden in Inclusive Distributions

The method of semi-exclusive searches is general:

- Resonances: X → diphotons, di-b, di-tau, triphoton, …
- Edge/Endpoints: X → di-object + MET
- Other structures: X interferes and creates wiggle or dip

Any such effect can be searched for

- Inclusively
- Semi-exclusively
  - And Higgs → bb shows why we have to do it!
  - Otherwise we are giving up some easy opportunities…

Systematic approach?

Physics Hidden in Total Cross Sections

Some BSM processes might contribute to SM cross-sections

- Electroweakinos contributing to WW

Lisanti & Weiner '11; Feigl, Rzehak & Zeppenfeld, '12; Curtin, Jaiswal, Meade, Tien '12,'13,'14; Rolbiecki & Sakurai '13

- Stop → top + low mass neutralino near threshold adds to tt

Czakon, Mitov, Papucci, Ruderman & Weiler '14

- Stop → bino → wino contributes to ttW, tth,…

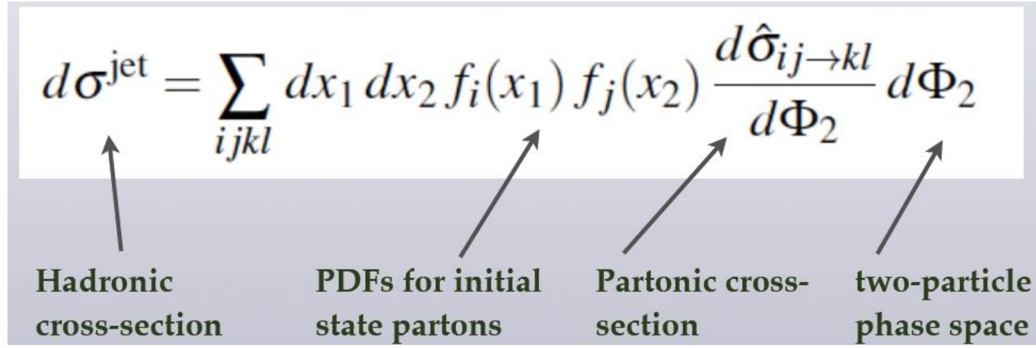
Cf. Huang, Ismail, Low & Wagner '15; Angelescu, Djouadi & Moreau '15; …

Are we properly cross-correlating all our measurements?

- Sidestep?
  - Spin effects:
    - the SM violates C and P maximally, BSM might be different

e.g. Han, Katz, Krohn & Reece '12

Ratios at different LHC collision energies



Old strategy:

- Compare physics at two values of s at same value of $\hat{s}/s = x_1\, x_2$
  - Pdfs almost the same
  - Partonic process changes (but often SM prediction scales with s)

Mangano & Rojo '12

- Compare physics at two values of s at same value of $\hat{s}$
  - Partonic process almost the same
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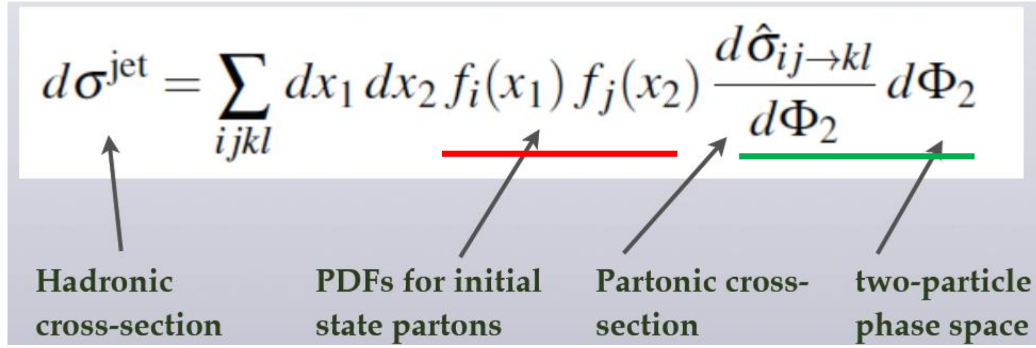

Old strategy:

- Compare physics at two values of s at same value of $\hat{s}/s = x_1\, x_2$
  - Pdfs almost the same
  - Partonic process changes (but often SM prediction scales with s)
    - But if a threshold between $x_1\, x_2\, s_{low}$ and $x_1\, x_2\, s_{high}$ then …

Mangano & Rojo '12

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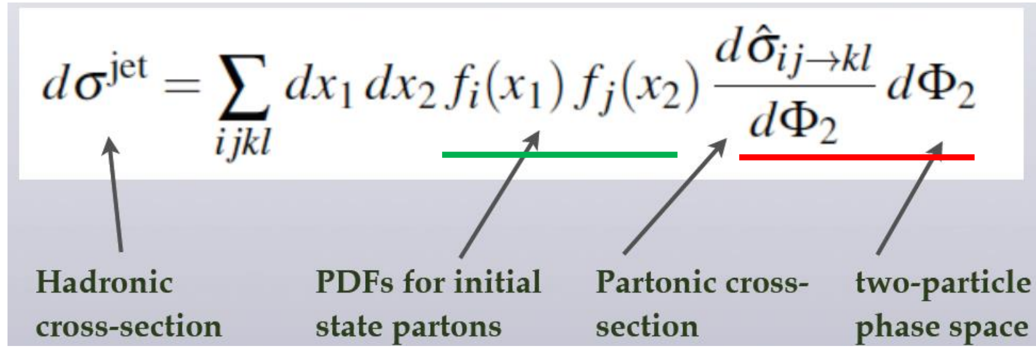
  - Partonic process almost the same
  - Pdfs change

Ratios at different LHC collision energies



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Mangano & Rojo '12

- Compare physics at two values of s at same value of $\hat{s}$
  - Partonic process almost the same
  - Pdfs change
    - But if a process subleading at s_{low} comes from different pdf…

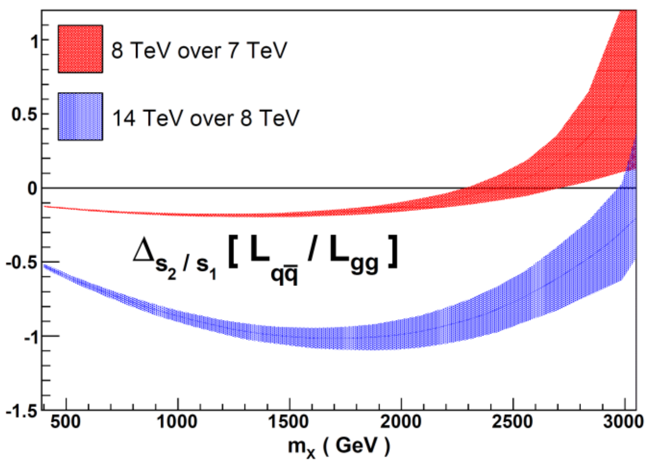
14 TeV
----
8 TeV

Ratio	$R^{\rm nnpdf}$	$\delta_{\rm PDF}(\%)$
$t\bar{t}/Z$	2.12	1.3
$t\bar{t}$	3.90	1.1
Z	1.84	0.7
W^+	1.75	0.7
W^-	1.86	0.6
W^+/W^-	0.94	0.3
W/Z	0.98	0.1
ggH	2.56	0.6
$t\bar{t}(M_{tt} \geq 1\ \rm TeV)$	8.18	2.5
$t\bar{t}(M_{tt} \geq 2\ \rm TeV)$	24.9	6.3
$\sigma_{\rm jet}(p_T \geq 1\ \rm TeV)$	15.1	2.1
$\sigma_{\rm jet}(p_T \geq 2\ \rm TeV)$	181.6	7.7

Mangano-Rojo ‘15

<1% - 7% variations with pdf, depending on ratio

Small variations among pdfs



$$\Delta_{E_1/E_2}(A) = 1 - \frac{A(E_2)}{A(E_1)}$$

Suppose there’s a broad resonance at 1.5 TeV producing tt-bar

At fixed s-hat, much more gg at 13 TeV than at 8 TeV; so qq-bar process suppressed

Thus precise predictions for ttbar at 13 vs 8 TeV will fail

Improvement: cancel luminosity uncertainty using ttbar/Z at the two energies.

Charge Asymmetries at the LHC

- Charge asymmetries arise from valence quarks
  - They measure degree of valence quark contribution to a process
    - (Or parity violation – *subtle point…*)

- These change as the center of mass energy changes and the rates (for particular event selections) should be well-predicted

  - Especially if we can normalize them intelligently to W* or W+j

- Useful in checking single top
- Would be useful in diagnosing BSM

- So energy ratios of charge asyms probably good as precision variables

Physics Hidden By Control Regions

- Away from tails, deviations typically not statistics limited
- Systematic uncertainties from control-to-signal extrapolation
  - How can these be reduced?
    - Attempts at precision measurements in control regions
    - Using theory at higher order to transfer to signal region
    - Additional questions (data and theory) in validation regions?
  - Large logs can appear in signal regions that are absent in controls?
    - Logs of HT/p_T^{min}
    - EW Sudakov corrections…
- Case studies??

Ratios on the Backbone

Play off statistical uncertainties versus systematic and theory uncertainties

- Tails give us highest-E sensitivity (but do we understand the tail?)
- Backbones give us highest level of control

For a dimension-six operator, tails, backbones and heads are comparable

- Cf. discussion following Mangano talk – they become complementary.

Tails win in dimension-8

For low-mass physics, backbones may win

- Wide resonance/wiggle
- Off-shell Higgs effects at high mass

Dibosons

with Chris Frye, Marat Freytsis, Jakub Scholtz '15

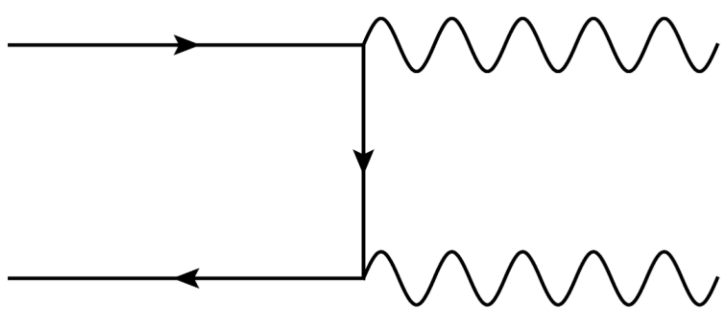
Production of any pair of photon, Z, $W^{\pm}$ (except same sign)

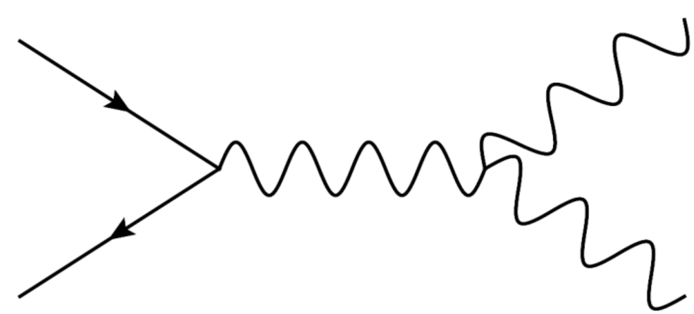
- Discrepancies have shown up – or not…
- Tails have low statistics; Head has resummation subtleties
- What ratios/variables might help on the backbone?

- Put high-energy $SU(2) \times U(1)$ structure to use
  - Leading-order (tree-level) partonic-level into nicer form
  - Notice useful ratios, show they are still useful in pp collisions

- Proceed to realistic situation for two neutral bosons
  - Show corrections beyond leading order are small at high energy
    - NLO
    - gg-induced NNLO
  - Show remaining uncertainties are small

- *All results below using MCFM Monte Carlo* Campbell, R.K.Ellis





$$a_1 \propto \mathcal{M}(xx) \propto \mathcal{M}(wx) \propto \mathcal{M}(ww_{\mathbf{1}}),$$

t,u

$$a_3 \propto \mathcal{M}(ww_{\mathbf{3}}),$$

s,t,u

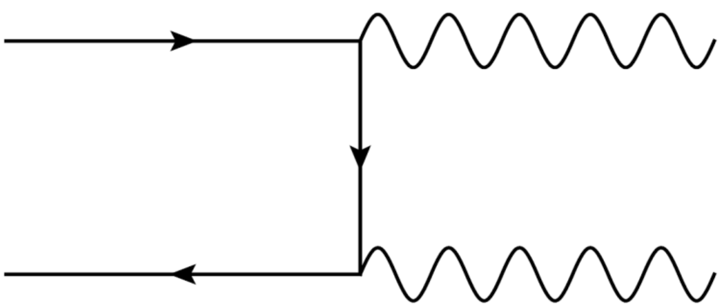
$$a_\phi \propto \mathcal{M}(\phi\phi),$$

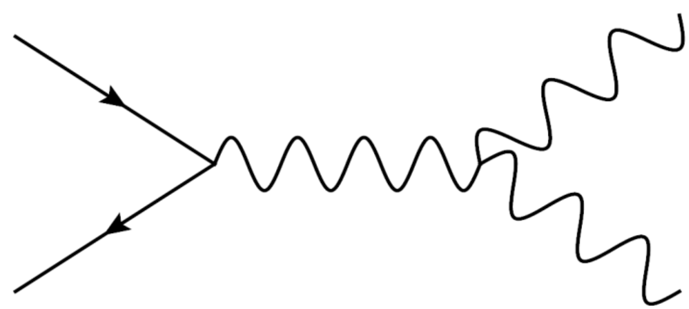
s

SU(2) w^a (a=1,2,3), *U(1)* x

- up to $(m_Z/E)^2$ terms

$$\gamma = c_W\, x + s_W\, w^3,$$
$$Z = c_W\, w^3 - s_W\, x,$$





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$$a_3 \;\propto\; \mathcal{M}(ww_{\mathbf{3}})\,,$$

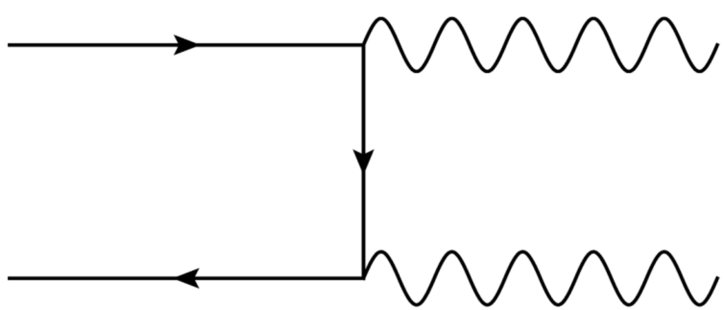
$$a_\phi \;\propto\; \mathcal{M}(\phi\phi)\,,$$

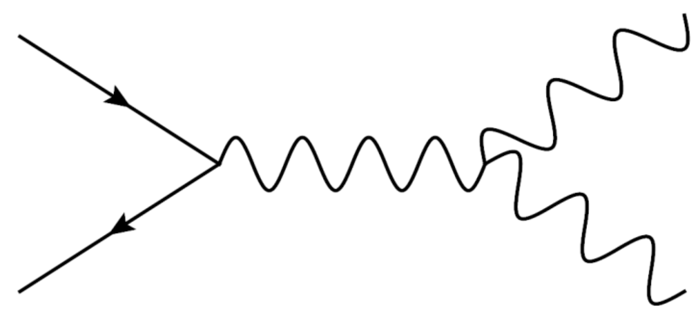
$$|a_1|^2 = \frac{\hat{t}}{\hat{u}} + \frac{\hat{u}}{\hat{t}}\,,$$

$$(a_1 a_3) = \left(\frac{\hat{t}-\hat{u}}{2\,\hat{s}}\right) + \frac{1}{4}\left(\frac{\hat{t}}{\hat{u}} - \frac{\hat{u}}{\hat{t}}\right)\,,$$

$$|a_3|^2 = \frac{\hat{t}\hat{u}}{4\,\hat{s}^2} - \frac{1}{8} + \frac{1}{32}\left(\frac{\hat{t}}{\hat{u}} + \frac{\hat{u}}{\hat{t}}\right)\,,$$

$$|a_\phi|^2 = \frac{\hat{t}\hat{u}}{4\,\hat{s}^2}\,.$$





ZZ, $Z\gamma$, $\gamma\gamma$ at Leading Order (@LO)

$$|a_1|^2 = \frac{\hat{t}}{\hat{u}} + \frac{\hat{u}}{\hat{t}}\,,$$

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q} \to V_1^0 V_2^0) = \frac{C_{12}^q}{\hat{s}^2}|a_1|^2\,,$$

$$C_{\gamma\gamma}^q = \frac{1}{2}\,\frac{\pi\alpha_2^2 s_W^4}{N_c}\,2Q^4\,,$$

$$C_{Z\gamma}^q = \frac{\pi\alpha_2^2 s_W^2 c_W^2}{N_c}\,\left(L^2Q^2 + R^2Q^2\right)\,,$$

$$C_{ZZ}^q = \frac{1}{2}\,\frac{\pi\alpha_2^2 c_W^4}{N_c}\,\left(L^4 + R^4\right)\,.$$

Couplings to Z :

$$L = T_3 - Y_L\,t_W^2\,, \qquad R = -Y_R\,t_W^2$$

ZZ, $Z\gamma$, $\gamma\gamma$ at Leading Order (@LO)

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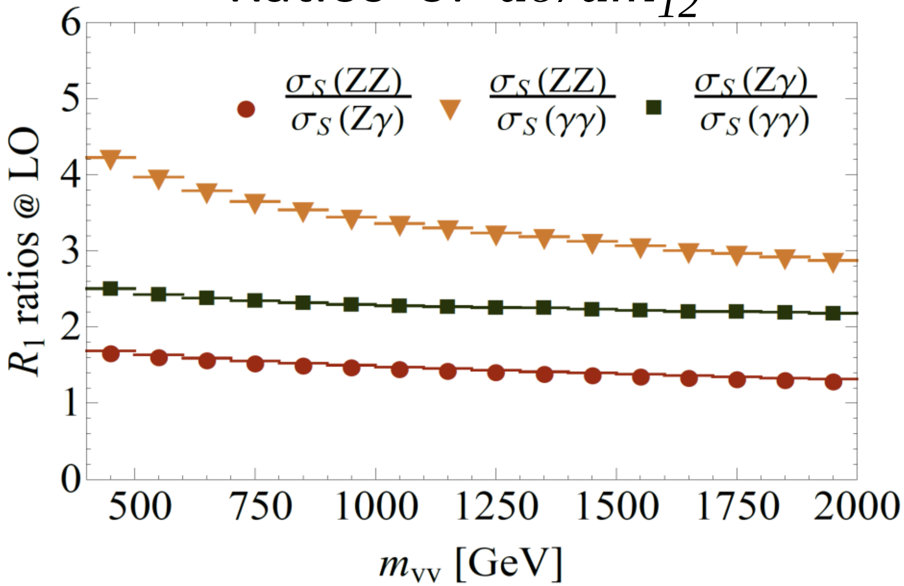
Ratios of $d\sigma/dm_{12}$



Couplings to Z :

$$L = T_3 - Y_L\, t_W^2 \,, \qquad R = -Y_R\, t_W^2$$

ZZ, $Z\gamma$, $\gamma\gamma$ at Leading Order (@LO)

$V_1^0 V_2^0$	$C_{12}^u \cdot 10^5$	$C_{12}^d \cdot 10^5$
$\gamma\gamma$	1.2	0.07
$Z\gamma$	2.2	0.7
ZZ	1.6	3.3

uu dominates;
PDF uncertainties
should cancel

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q} \to V_1^0 V_2^0) = \frac{C_{12}^q}{\hat{s}^2}|a_1|^2 ,$$

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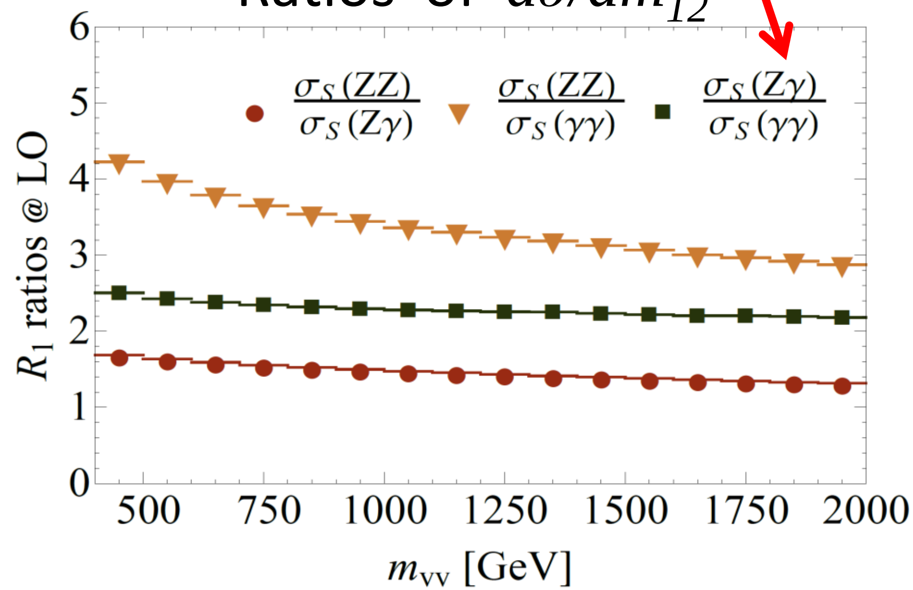
Ratios of $d\sigma/dm_{12}$

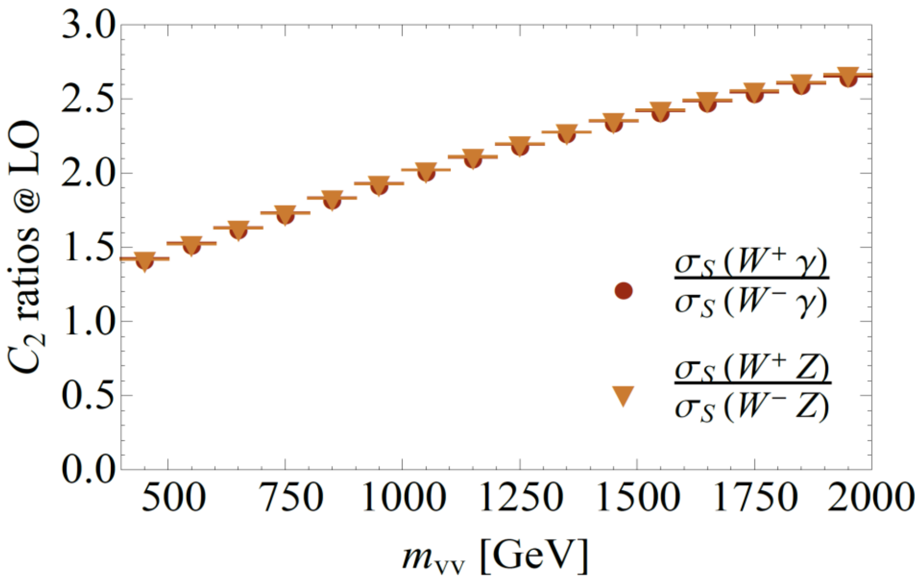


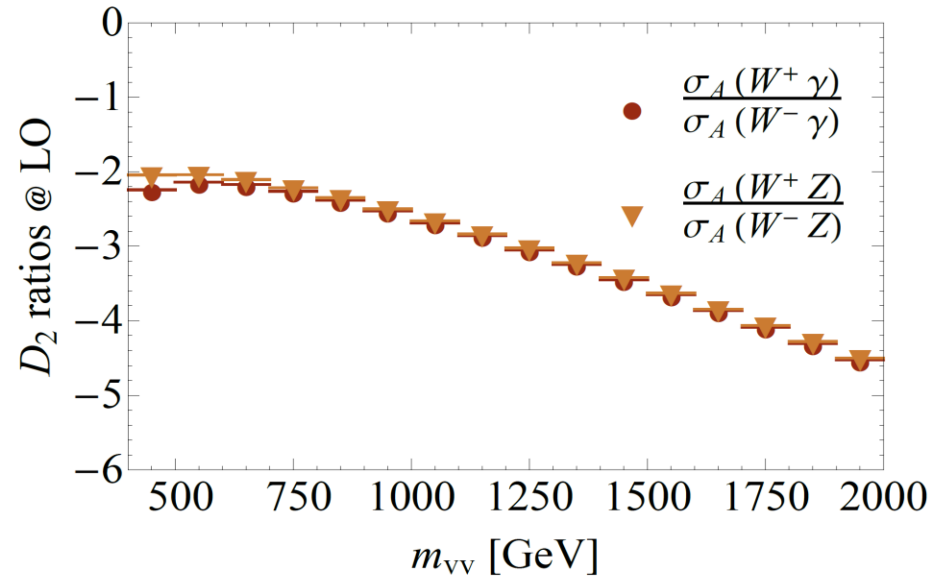
Couplings to Z :

$$L = T_3 - Y_L\, t_W^2 , \qquad R = -Y_R\, t_W^2$$

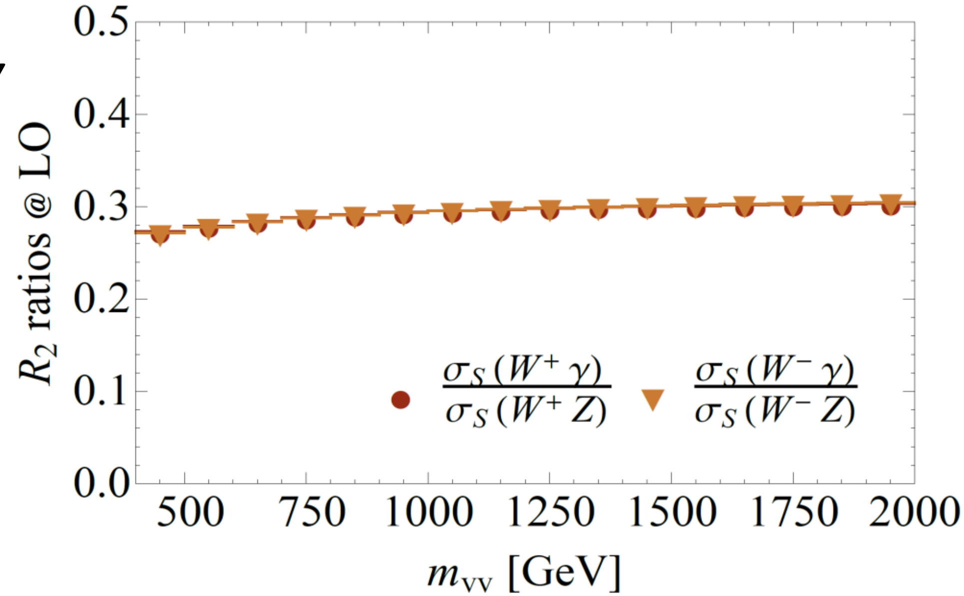
Charge asymmetries for $W\gamma$,WZ are related

- Determined by the pdfs for both sym, antisym FB quantities



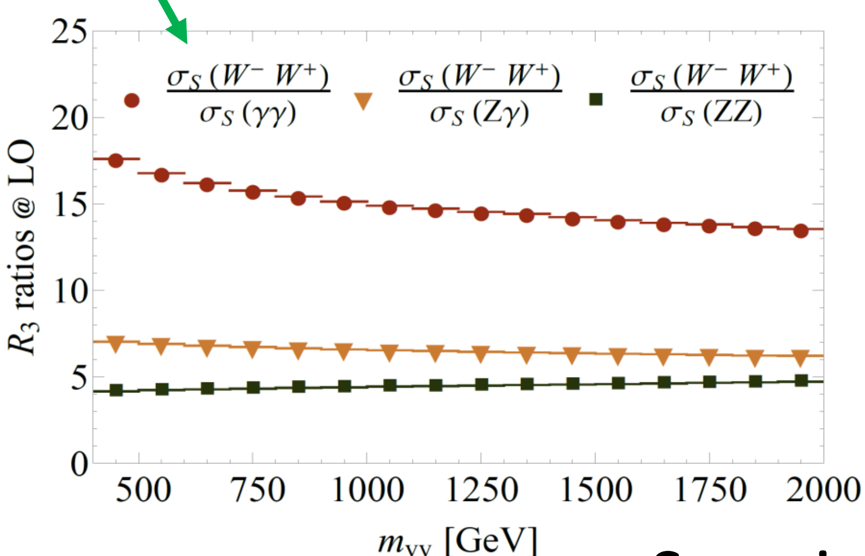


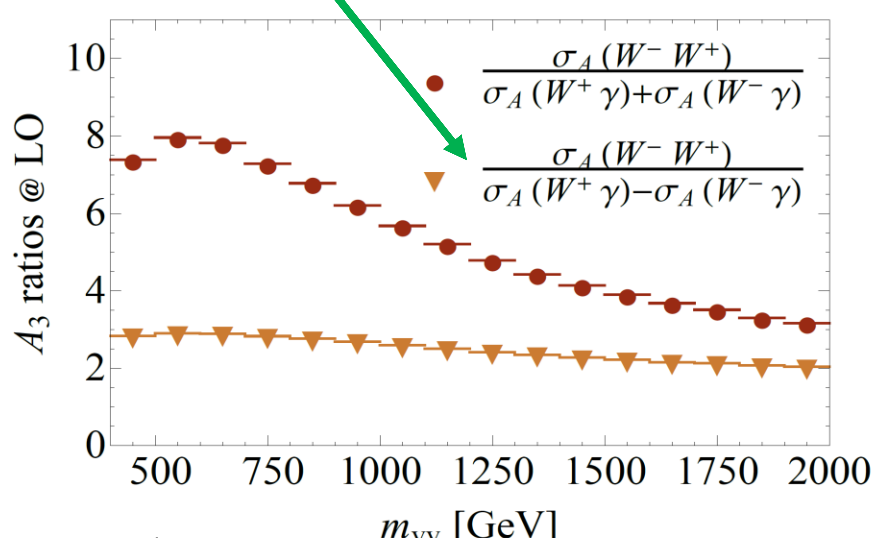
More $W^{\pm}V$



Best statistics

Best statistics and LO PDF behavior





Surprising $W^+ W^-$

Beyond Leading Order?

- What about higher-order corrections?
  - QCD cancellations?
    - How large are the shifts in the ratios?
    - *SU(2)xU(1)* relations should help -- Where do they fail?
    - What uncertainties remain?
  - EW corrections - Partial cancellations?

- Big issue: the radiation zero
  - Where important, LO *SU(2)xU(1)* relations may receive large corrections

- Start with $\gamma\gamma$, $Z\gamma$, ZZ
  - No radiation zero
  - Events fully reconstructed (Z → leptons ONLY here)
  - Good statistics for first two

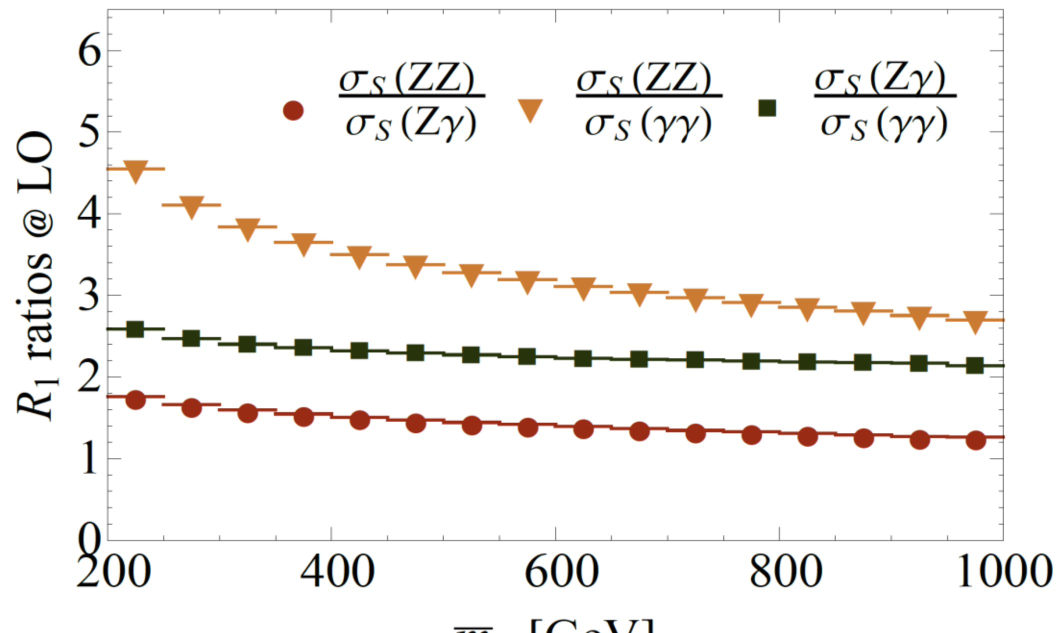
$ZZ, Z\gamma, \gamma\gamma$ at LO ➔ NLO

- Must choose observable carefully to avoid large NLO corrections

$$\overline{m}_T = ½[\ m_{T1} + m_{T2}\ ] = \text{min energy at } 90^o \text{ scattering}$$

- Radiation cannot reduce this variable
  - so no region of NLO phase space is secretly LO.

Ratios of $d\sigma/dm_T$



ZZ, $Z\gamma$, $\gamma\gamma$ at LO ➔ NLO

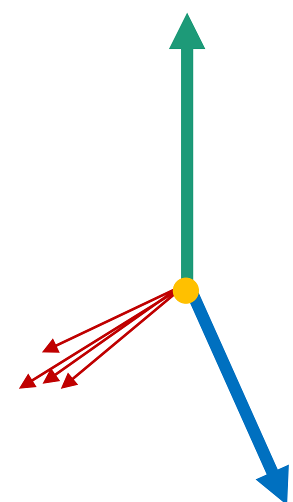
- Need to choose cuts carefully to avoid large NLO corrections
  - Assure cuts select kinematics similar to LO
    - i.e. no vector bosons softer than jets (cf. giant K factors)
  - But do not impose drastic jet veto

- We take

$$p_T^{jet} < \tfrac{1}{2}\, p_T^V\big|_{min} \;;\; \tfrac{1}{2}\, p_T^V\big|_{min} > \tfrac{1}{2}\, p_T^V\big|_{max}$$

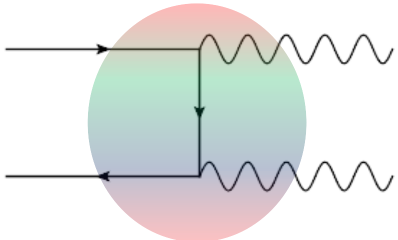
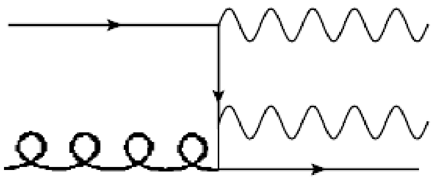
Notice these cuts scale –

no large logs at high E

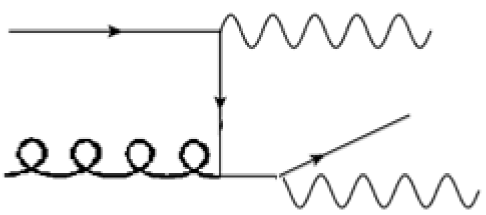


ZZ, $Z\gamma$, $\gamma\gamma$ at LO ➔ NLO

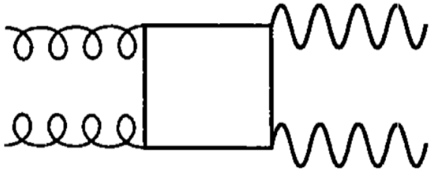
- QCD corrections treat Z, γ identically, largely cancel…

- …except…
  - Collinear quark-boson regime
    - Photon has log enhancement
    - Z has no enhancement

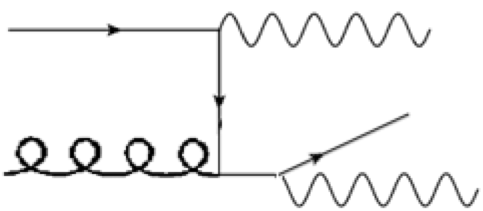


  - Gluon fusion process (formally NNLO but numerically large)

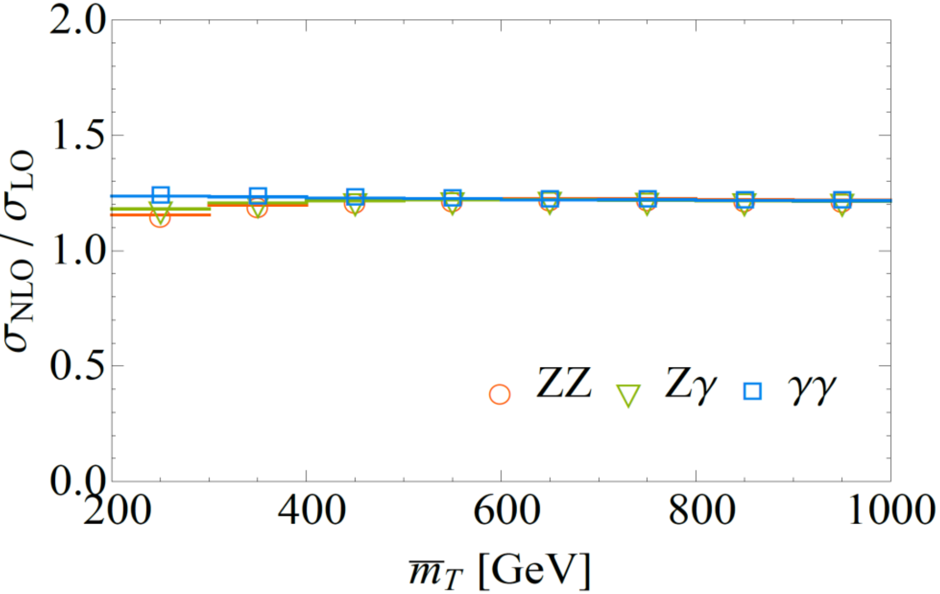


- Both of these driven by gluon pdf
  - Both decrease in importance at high energy

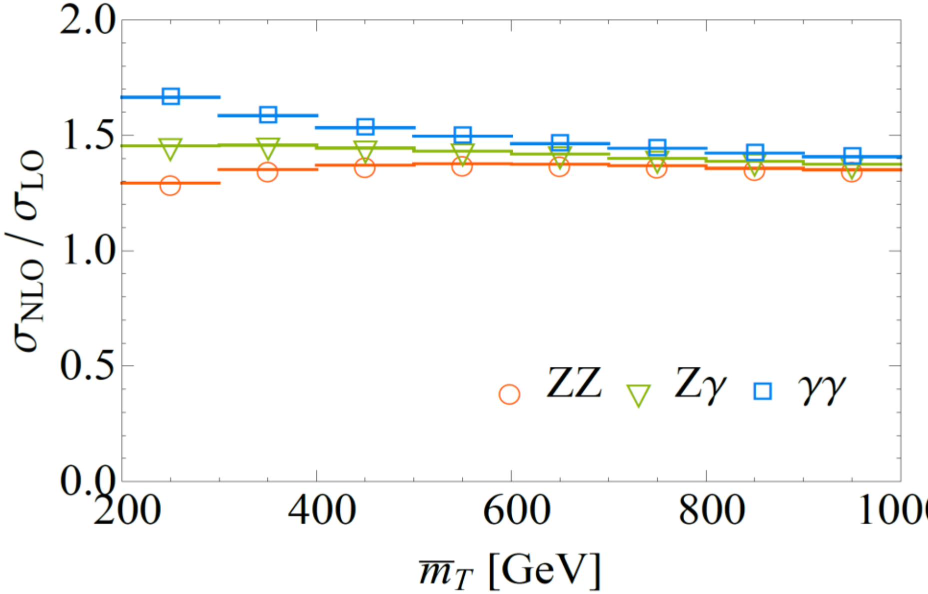
NLO/LO K factors



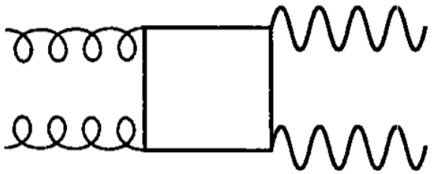
Collinear region cut away



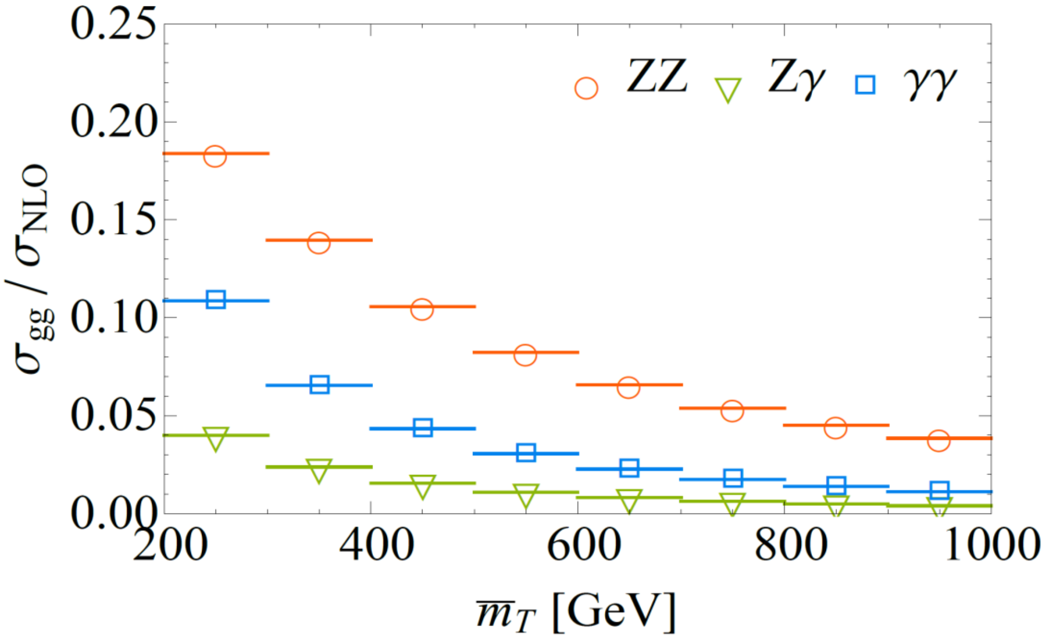
Collinear region included



NNLO gg / NLO partial K factor

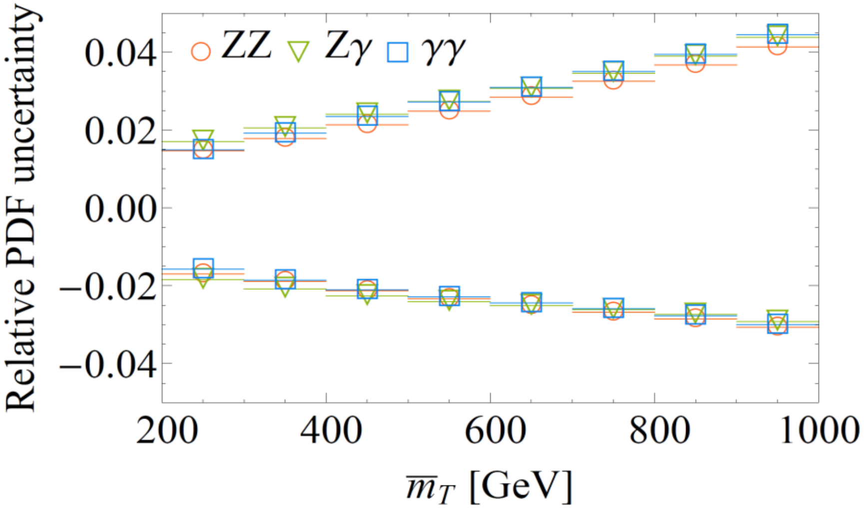


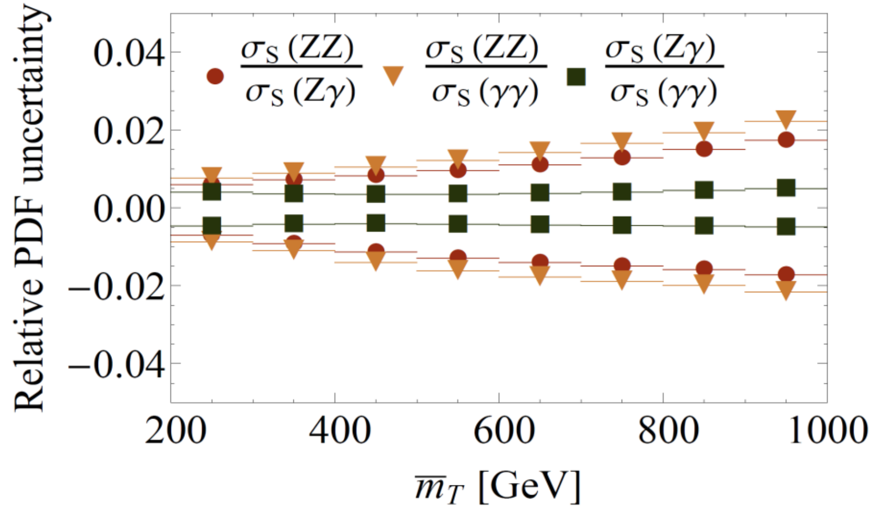
gg gives largest NNLO correction to ratios



- To set scale on gg use partial knowledge of NNNLO gg correction
  - (backup slide)

PDF Uncertainties

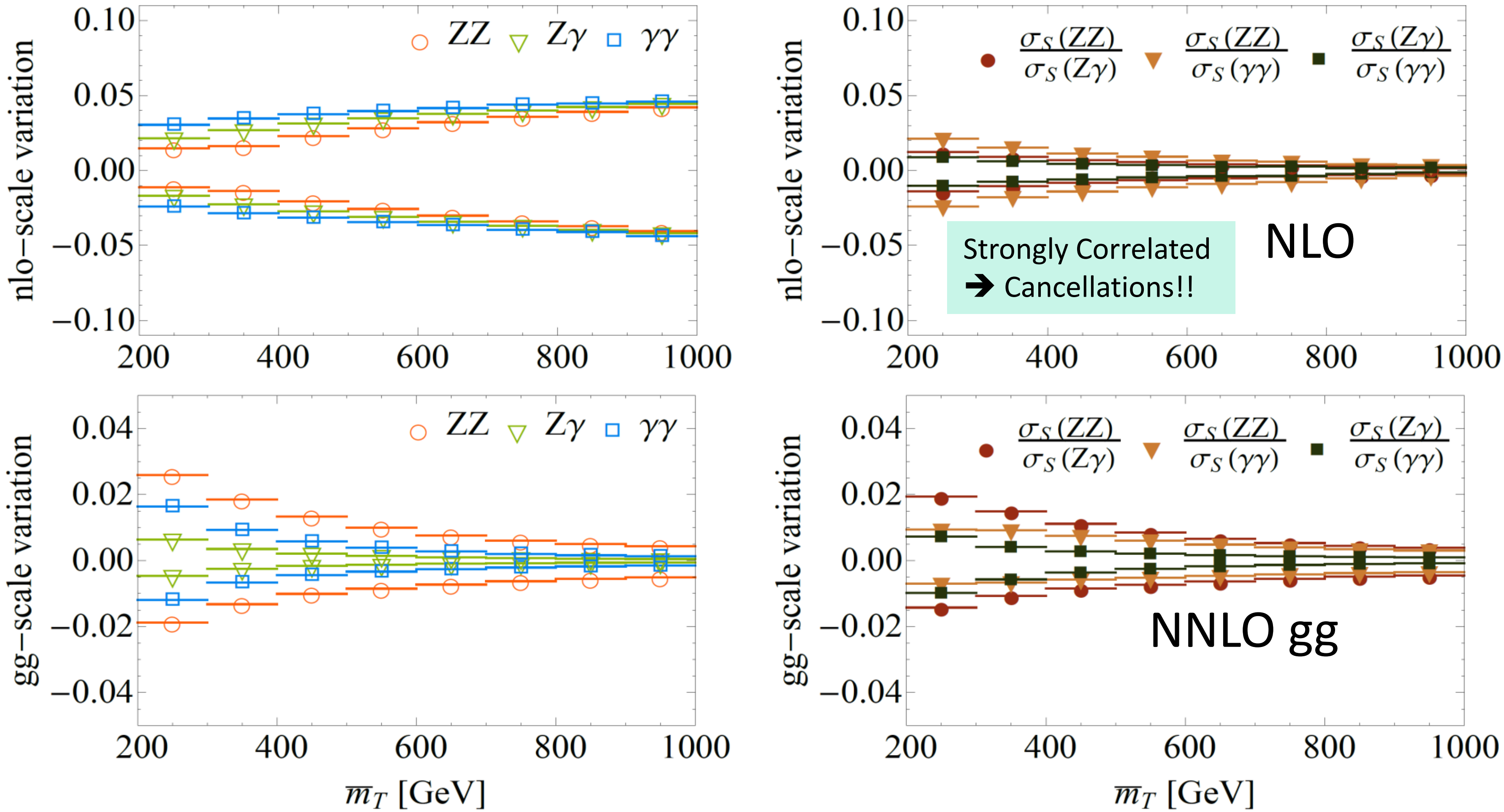




- Much smaller in ratios
  - 1 – 2 %
  - Especially for $Z\gamma$ / $\gamma\gamma$

Scale [next-order] uncertainties

- Estimates NNLO corrections to what is already present at NLO



- Does not account for new channels (e.g. *q q* → *q q V V* ~ 2–3%)

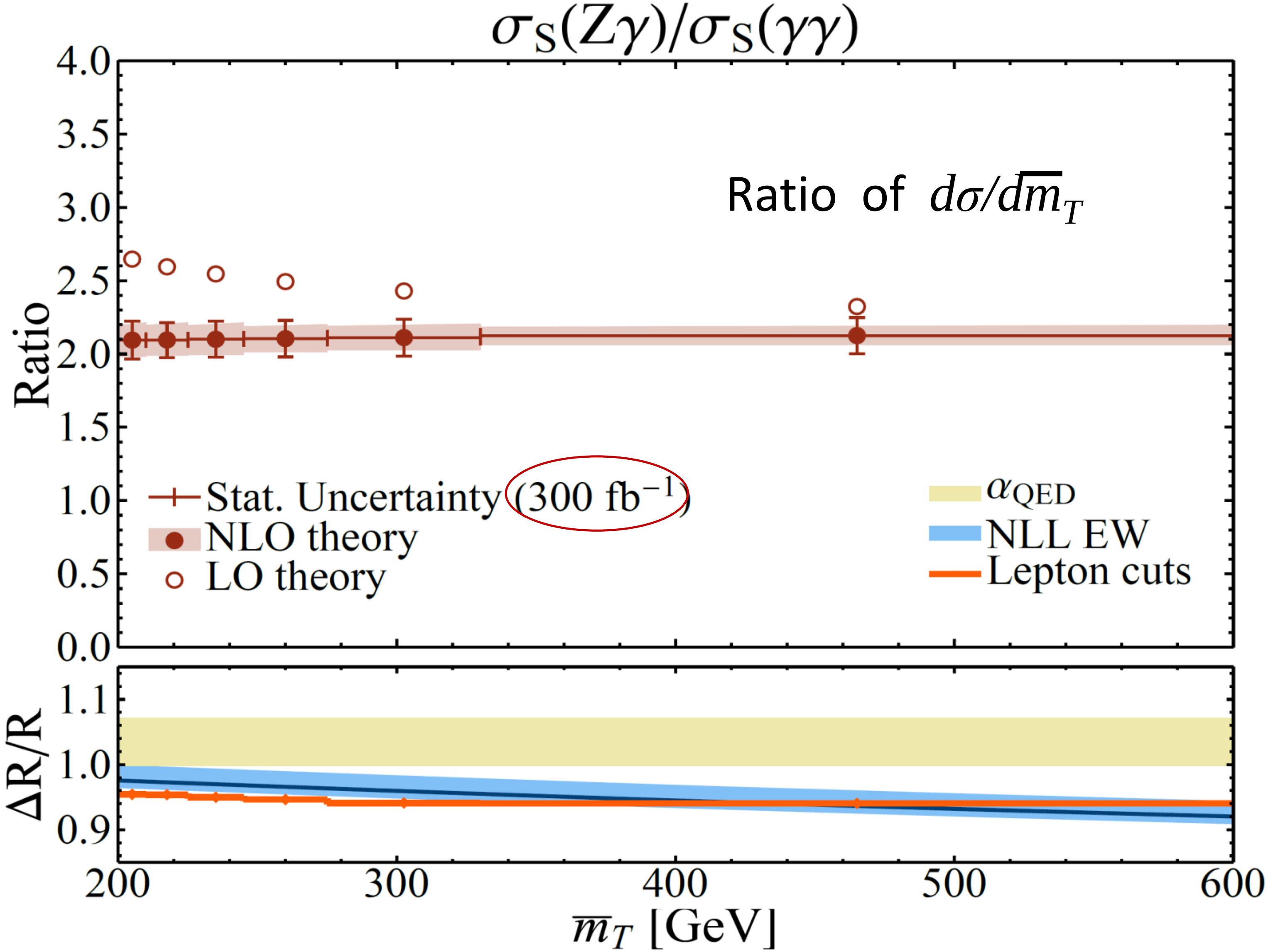
Experimental effects

- Some experimental issues cancel
  - Luminosity
  - Jet energy scale

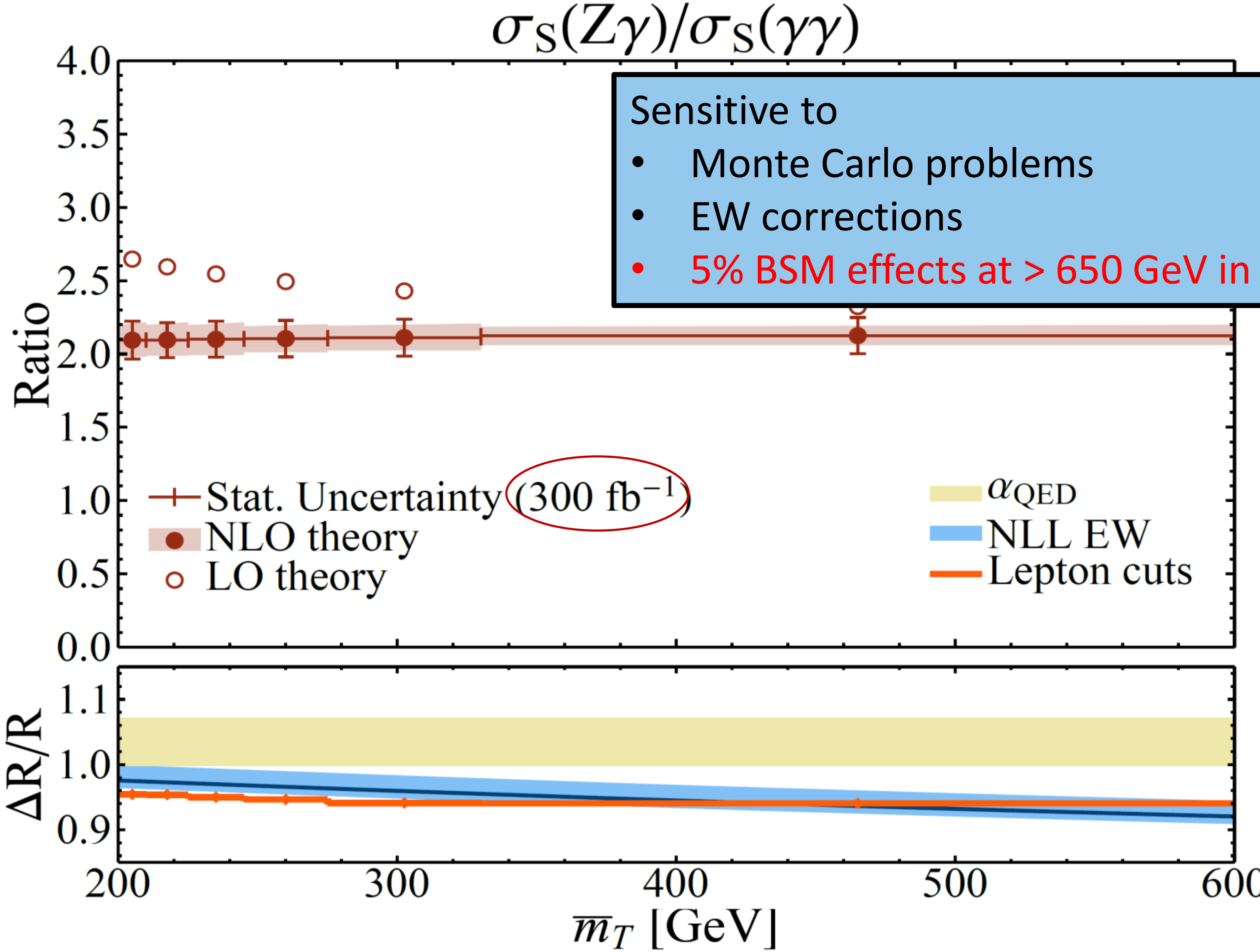
- Some don't:
  - Z → leptons – leptons have their own cuts, acceptance
      - Or → neutrinos -- other issues
    - Can be a substantial effect at low pT
    - But can model, measure with low absolute uncertainty
  - Z – finite width [experimental definition of "Z"]
    - Not large effect
    - Can model

Uncertainty budget

Effect	R_{1a} $(Z\gamma/\gamma\gamma)$	R_{1b} $(ZZ/\gamma\gamma)$	R_{1c} $(ZZ/Z\gamma)$	Comments
$qq \to VVqq$	2–3%	3–3.5%	1.5–2.5%	extrapolating $p^j_{T,\min} \to 0$ (Sec. 4.2)
μ_R, μ_F (gg)	0.5–1%	1%	1–2%	uses NLO $gg \to \gamma\gamma$ (Sec. 4.5)
μ_R, μ_F (NLO)	0.5–1%	1.5–2.5%	1–1.5%	varied independently (Sec. 4.5)
PDF	0.5%	1–1.5%	0.5–1%	MSTW 2008 using MCFM (Sec. 4.5)
NLO EW	$^{+2\%}_{-1\%}$	$^{+3\%}_{-1\%}$	$^{+2\%}_{-1\%}$	EFT scale uncertainty (Sec. 4.4.1)

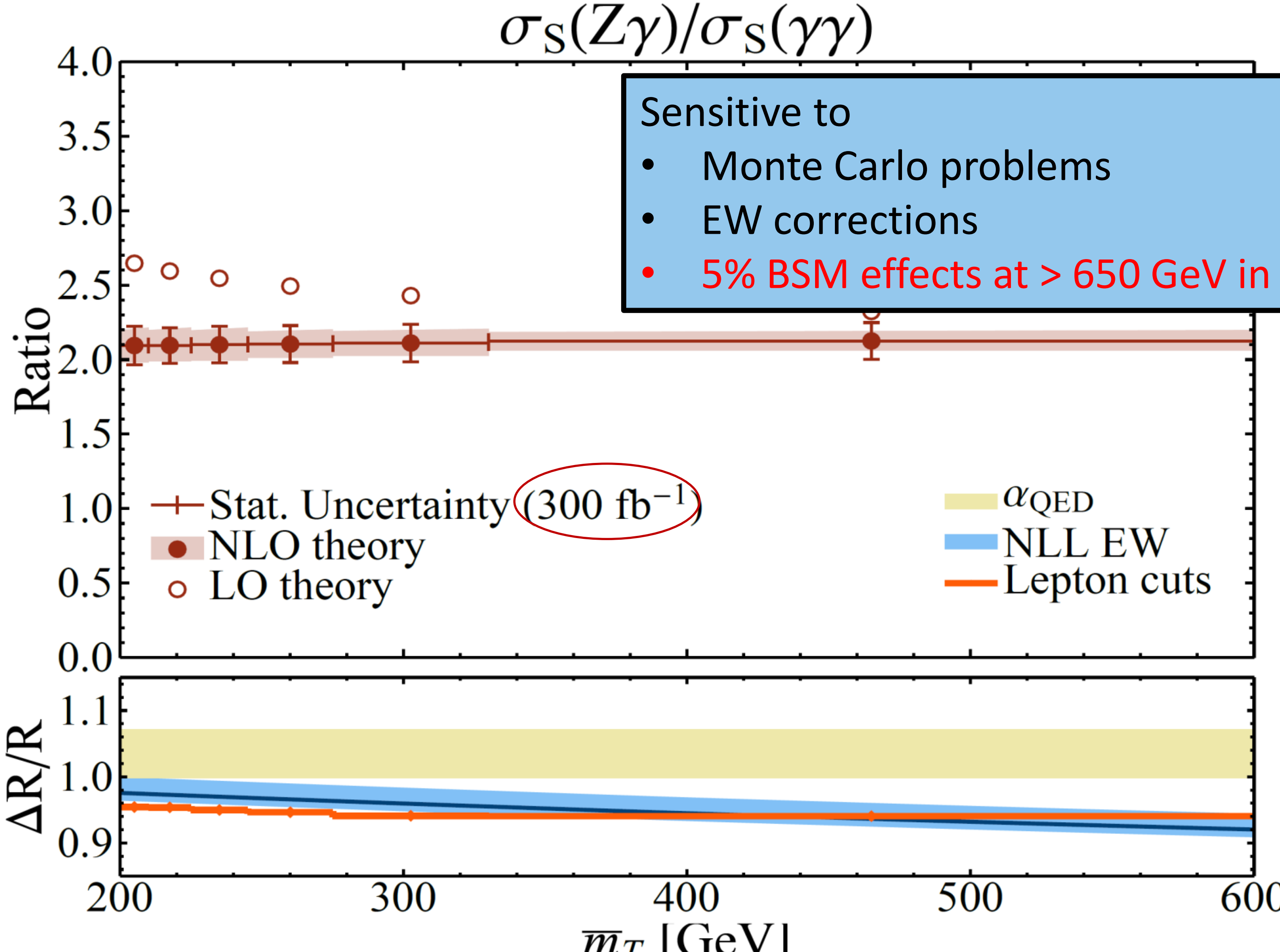


$\sigma_S(Z\gamma)/\sigma_S(\gamma\gamma)$
Ratio of $d\sigma/d\overline{m}_T$
Ratio
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Stat. Uncertainty (300 fb^{-1})
NLO theory
LO theory
α_{QED}
NLL EW
Lepton cuts
$\Delta R/R$
1.1
1.0
0.9
200
300
400
500
600
$\overline{m}_T$ [GeV]



Sensitive to

- Monte Carlo problems
- EW corrections
- 5% BSM effects at > 650 GeV in EW sector



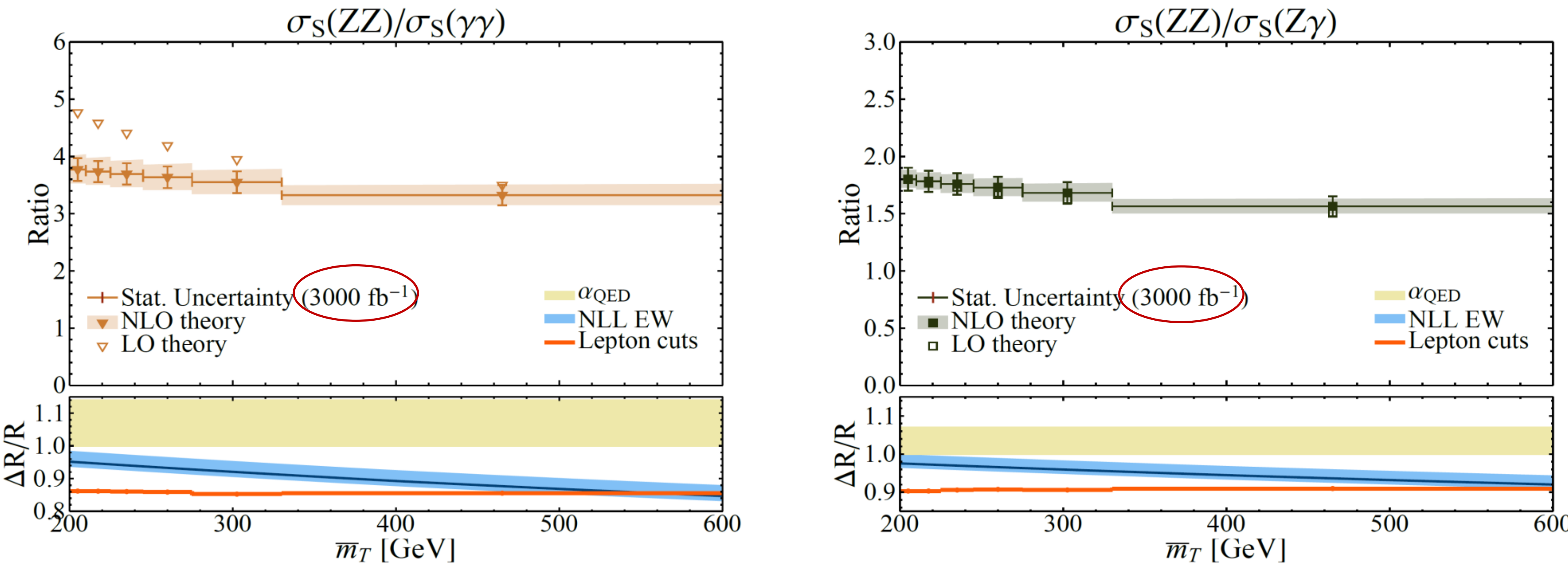
Sensitive to

- Monte Carlo problems
- EW corrections
- 5% BSM effects at > 650 GeV in EW sector

Possible Improvements:

- Use Z → neutrinos?
- Use Z → jets??
- At 3000 fb^{-1}, tens of bins, last bin probes > 1.2 TeV at 5%

The other ratios, at 3000 fb^{-1}



Probably want to include Z → neutrinos at price of higher theoretical uncertainty.

Compare backbone to tails

- If you're looking for dimension-6 BSM effect, tail and backbone similar sensitivity.
  - Pdf luminosity roughly falls with a power of s
  - Dim-6 effect roughly grows with power of s
- Unfortunately *(to be confirmed)* anomalous gauge couplings are
  - Dimension six (longitudinal bosons) but suppressed
  - Dimension eight
- But even if this particular effect only on tails,
  - Precise diboson MC can be tested using ratios
  - Electroweak effects (big on tails) can be tested without much QCD pollution
- And other BSM effects can appear on the backbone

Conclusions

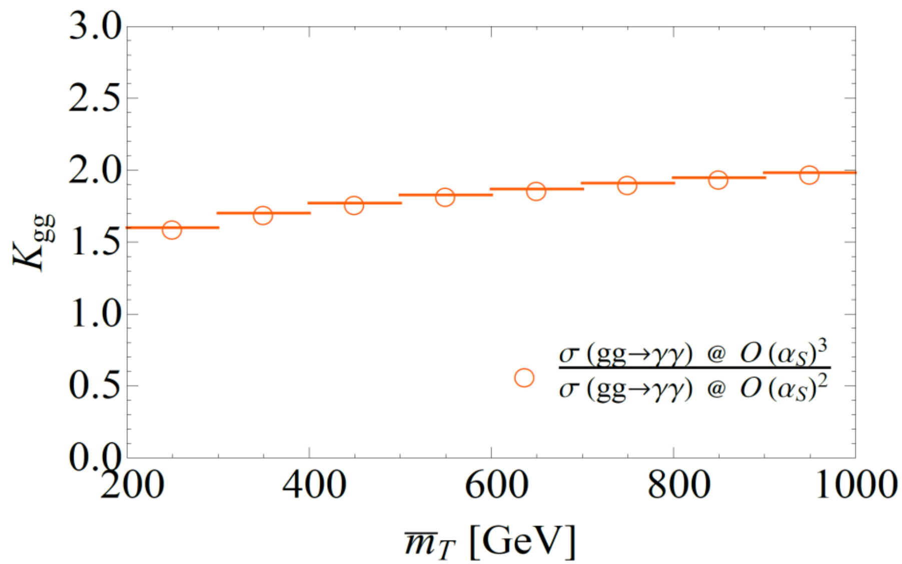
- It's not whether to look in the bulk, but how best to do it
  - High statistics can be in your favor, if you can reduce systematics
  - High statistics can be against you; cut wisely (go onto an orthogonal tail)

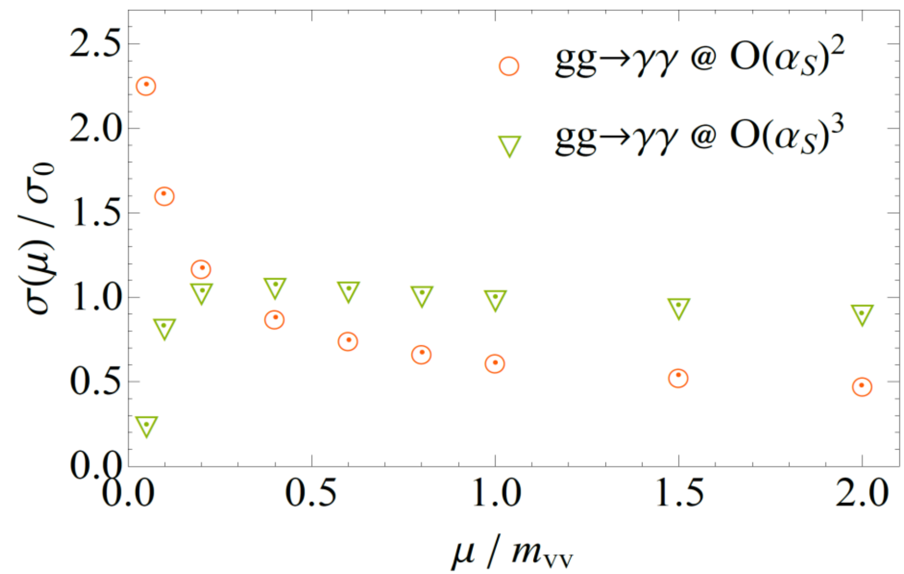
- Look for buried treasure (*inclusive is not conclusive*)
- Compare 8 TeV and 13 TeV cleverly *(cross-sections; charge asyms?)*
- Control the control regions *(and the transfer to signal regions)*

- New EW/hidden/rare physics requires high precision in bulk
  - Exercise: get high precision in diboson ratios at $p_T \gg M_W$
    - Ratios: small QCD corrections & uncertainties at high energy
    - Certainly good for SM studies (MC and EW)
    - Need still to learn more about how sensitivity to BSM is improved
      - Searches on high-E tails vs. precision at moderate E

Scale setting for gg loops

- For $gg \rightarrow \gamma\gamma$





- For the other processes

$$K_{gg} \equiv \frac{d\sigma_{(3)}(gg \to \gamma\gamma)}{d\sigma_{(2)}(gg \to \gamma\gamma)} \approx \frac{d\sigma_{(3)}(gg \to Z\gamma)}{d\sigma_{(2)}(gg \to Z\gamma)} \approx \frac{d\sigma_{(3)}(gg \to ZZ)}{d\sigma_{(2)}(gg \to ZZ)}$$