Digging Deep at the LHC

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First Glance beyond the Energy Frontier

September 7, 2016

Digging Deep

- Is the SM a complete description of LHC physics?
  - No?
  - Yes?
  - Don't know? *Not good…*

- Is naturalness a correct principle guiding the TeV scale?
  - QFT dynamics controls physics?
  - History of the universe confounds QFT expectation?
  - Just anthropics in the end?

Both of these require comprehensive search strategy

- Need for efficient strategy, broad approach, high precision

Where are we?

- SM-like Higgs akin to Michelson-Moreley MJS, ‘12
  - Null experiment – absence of clues
  - Flies in face of well-established understanding
    - We DO understand QFT and naturalness theoretically
    - Naturalness works in QCD
    - Naturalness works in condensed matter
  - Not obvious if a small problem or a big one
  - Not obvious what experiments to do next

- Could this just all be anthropics?
  - Could there be a landscape of vacua? Sure.
  - Is SM all determined by simply demanding a habitable vacuum? No.

No, it’s NOT Anthropics at the LHC

(Or if it is, it’s much more interesting than it would naively seem…)

- Anthropics might explain the cosmological constant.
  - Argument is general
  - Many fundamental theories might easily satisfy its premises
- But anthropics cannot <u>by itself</u> explain naturalness puzzle
  - Required premises strain credulity
  - No known fundamental theory would satisfy its premises
  - Even hard to imagine how it could, given what we know
  - “Artificial Landscape Problem”

Where I'm going

- Goal of this anthropic argument:
  - NOT: predict c.c. or electroweak mass scale within order of magnitude
  - ONLY: predict very general features of the universe on very general grounds
  - BUT: claim that anthropics predicts
    - A small c.c.
    - A large **natural** hierarchy – not an unnatural one
  - THEREFORE: **Anthropics does not solve the naturalness problem**
  - ➔There is something to find!
    - More pheno at LHC (or elsewhere) than just SM

- What about existing anthropic solutions to naturalness problem?
  - The premises of these solutions violate the premises of my argument
  - The violation introduces a new problem, as bad as the naturalness problem
    - "Artificial landscape problem"
  - Merely replacing naturalness problem with artificial landscape problem

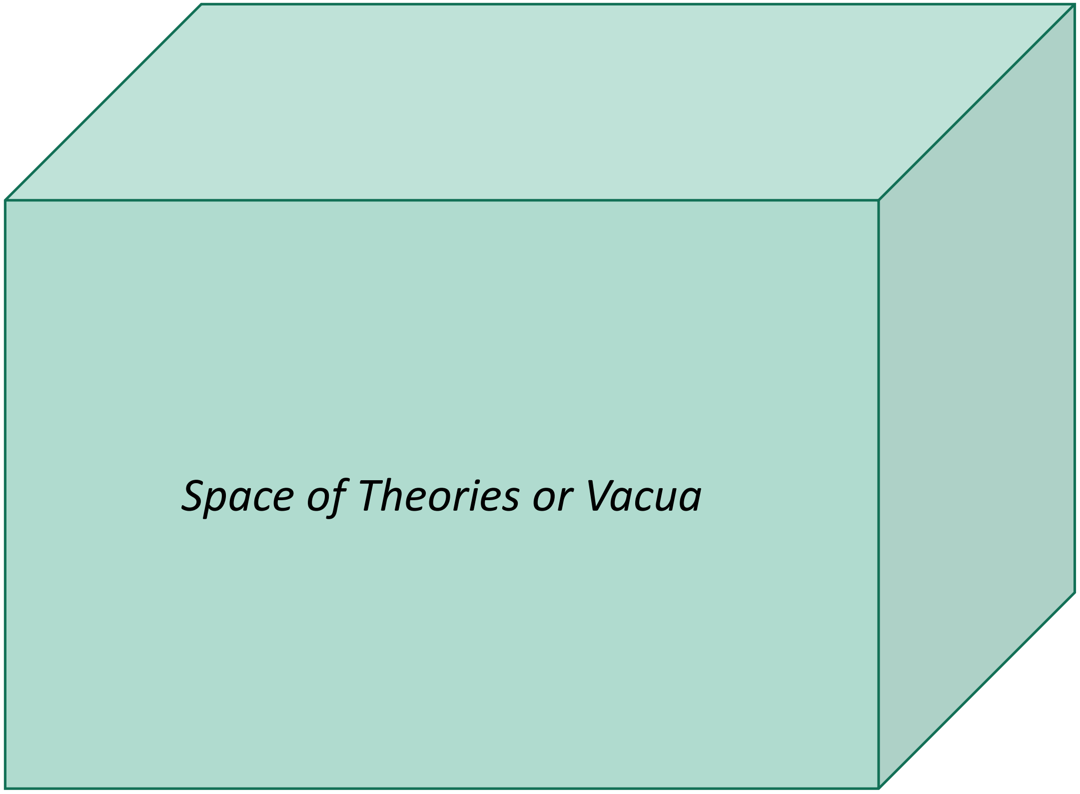
Starting assumptions

- A landscape of vacua
    - Gravity in all vacua (4d?)
    - Some of these vacua have small c.c., most don’t.
    - Some of these vacua have hierarchies, most don’t
        - Of those that have hierarchies, some are unnatural, most aren’t

Should we accept these premises?

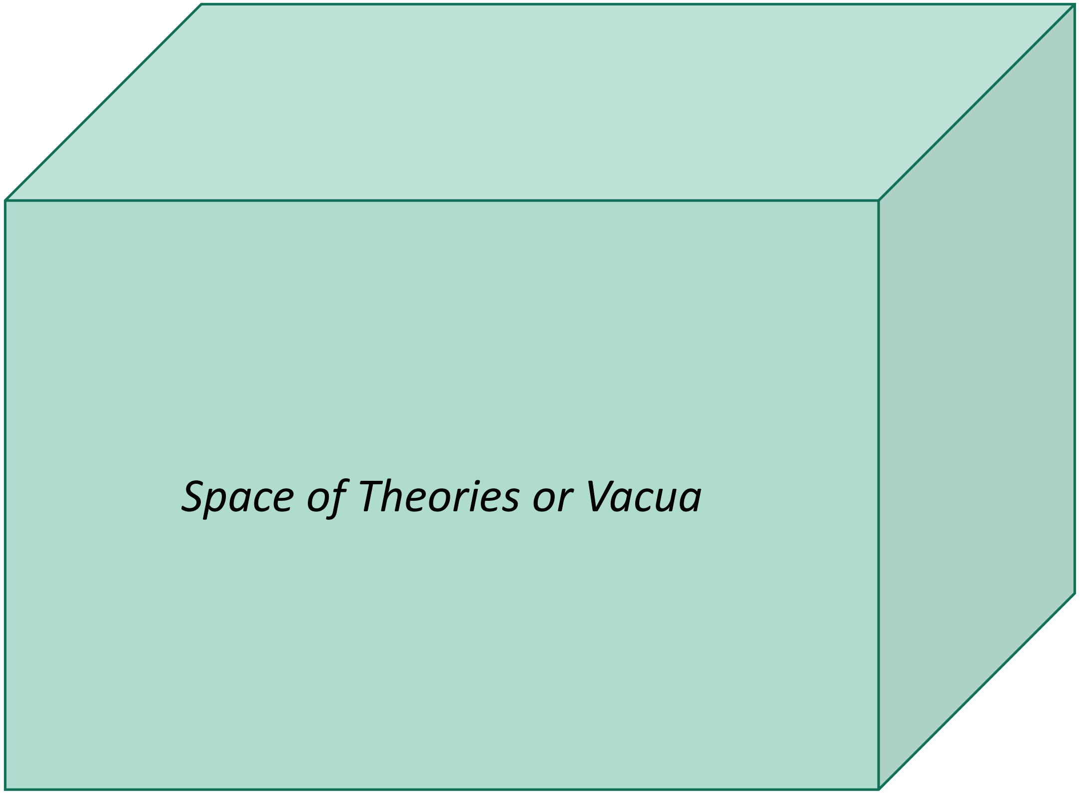
- The naturalness problem: Most hierarchies aren’t natural
- Hierarchies aren’t hard to achieve but aren’t completely generic
    - *SUSY and SUSY-breaking hierarchies*
    - *Technicolor and other dynamical hierarchies*
    - *Small Yukawas (weakless; flavor hierarchies)*
    - *Vectorlike fermions (technically natural)*
- If cc couldn’t be large, there’s no cc problem anyway
- If gravity absent, both problems evaporate

Anthropic Argument



Anthropic Argument

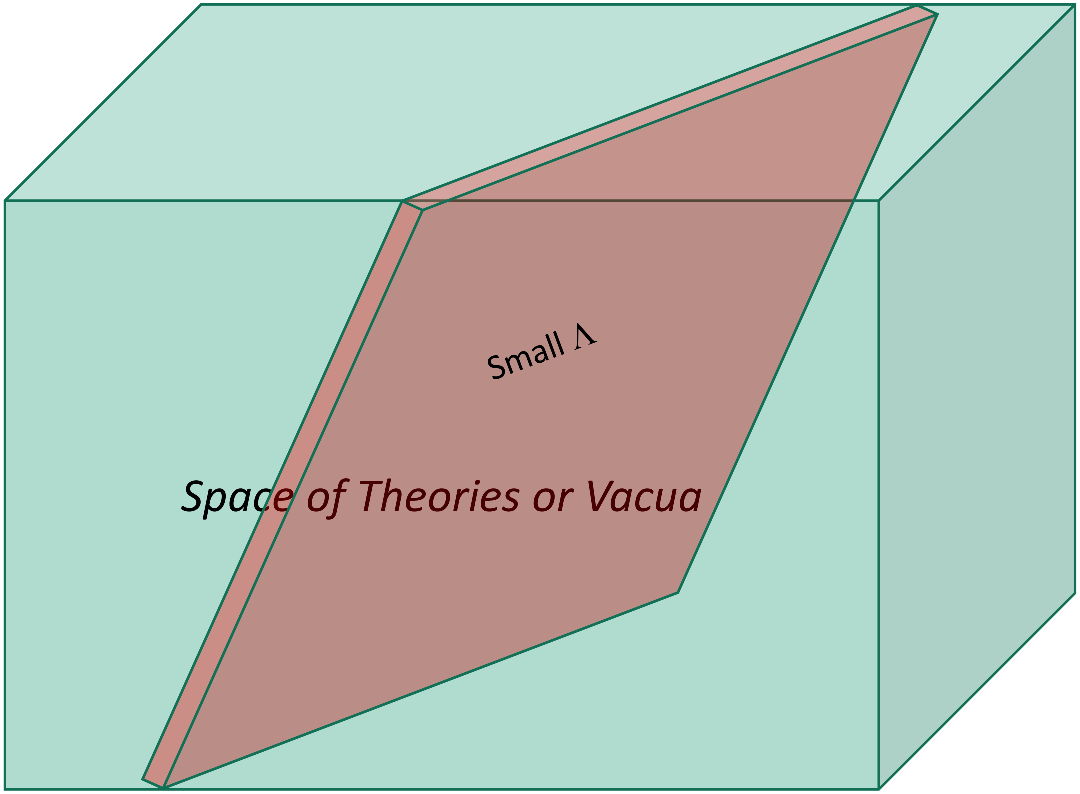
- (Despite the drawing, this space is a discrete set, not continuous)



Anthropic Argument

1. Small Cosmological Constant

    (Structure must form)



Anthropic Argument

1. Small Cosmological Constant
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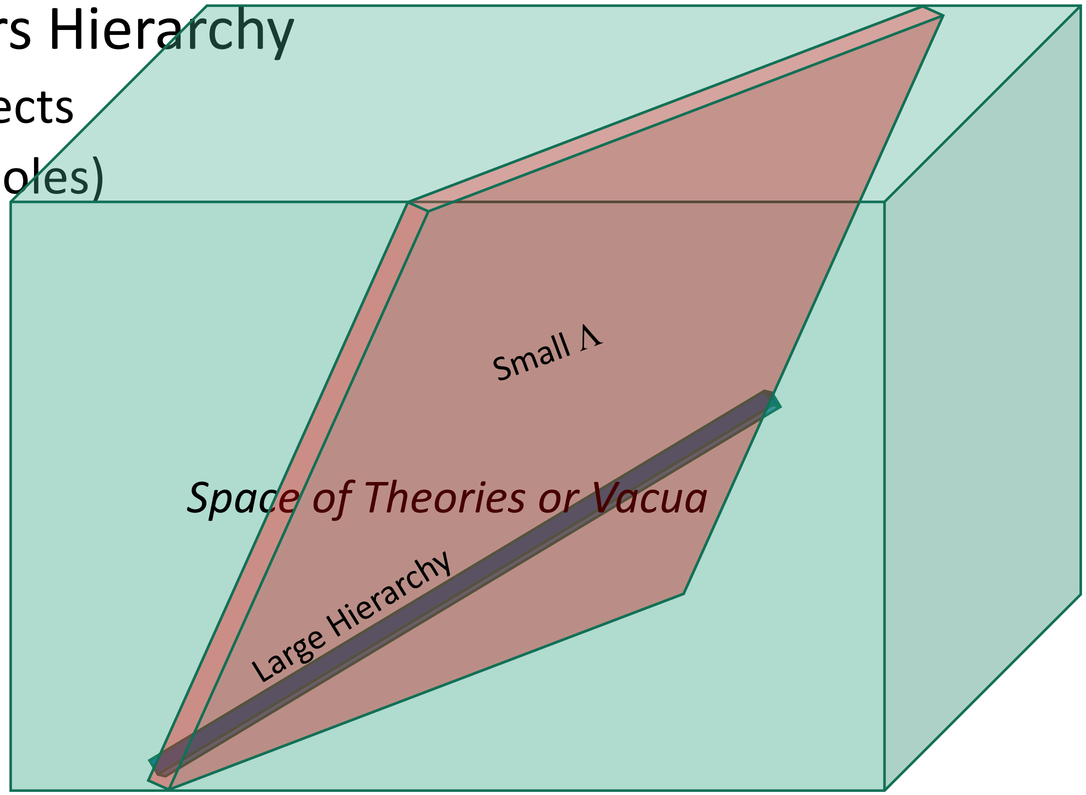
2. Large Gravity-to-Others Hierarchy
   (Must have large objects
   that are not black holes)



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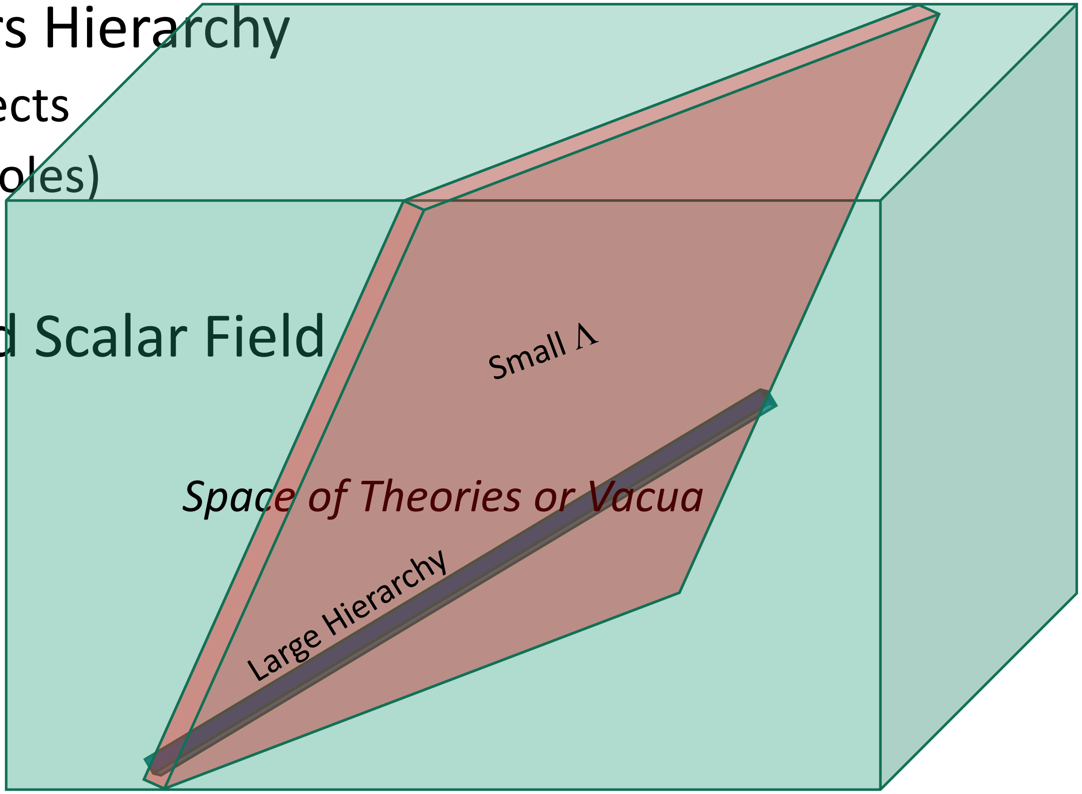
3. Very Light Unprotected Scalar Field

???



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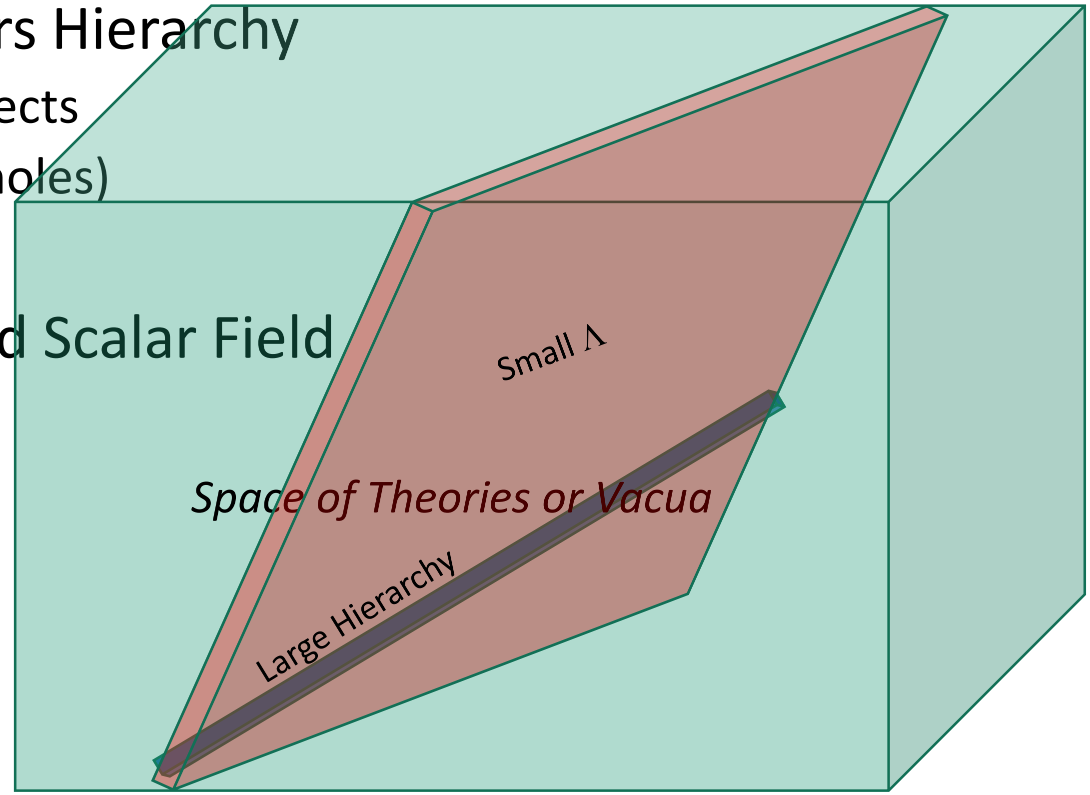

Why should Theories/Vacua with small CC and large hierarchy ALSO COMMONLY have a light scalar?

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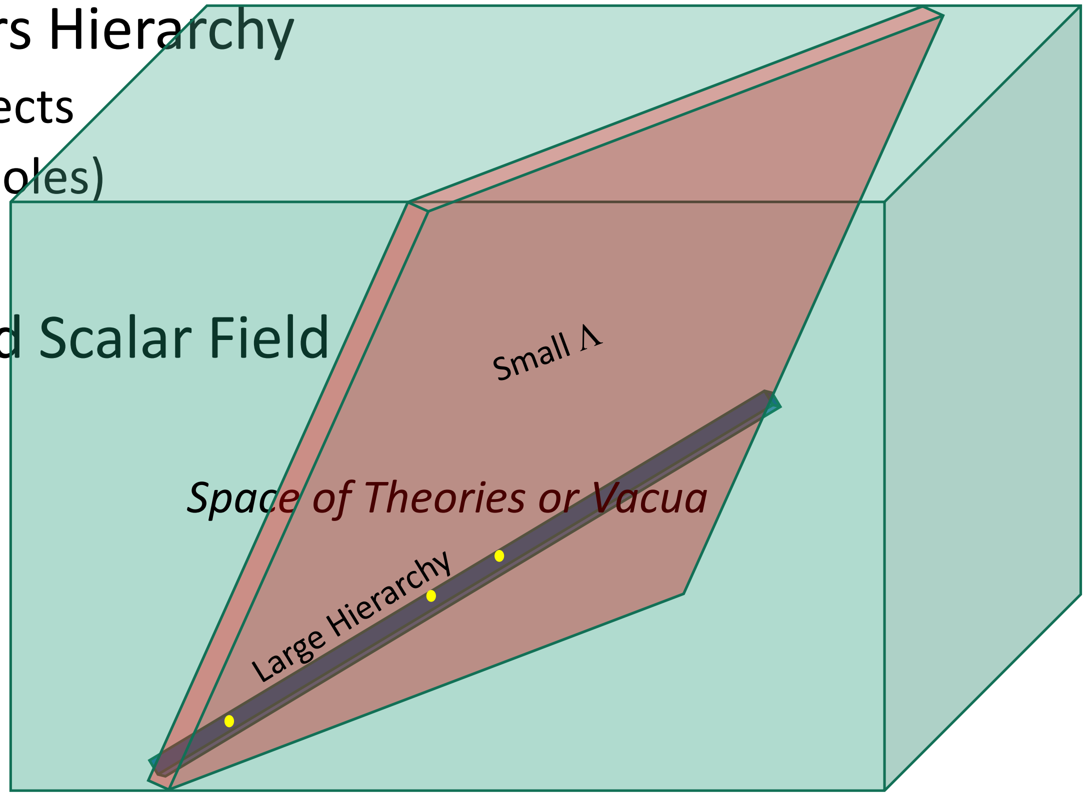


The Argument, Again

- Observers need some space and a lot of time

➔ need small cosmological constant

➔ cosmological constant must be small

- Observers need complexity

➔ need simple objects that are massive but don't form black holes

➔ need hierarchy of masses between M_{pl} and other objects

- Observers need X

➔ need X' to assure X

➔ need hierarchy to arise from a light unprotected scalar to assure X'

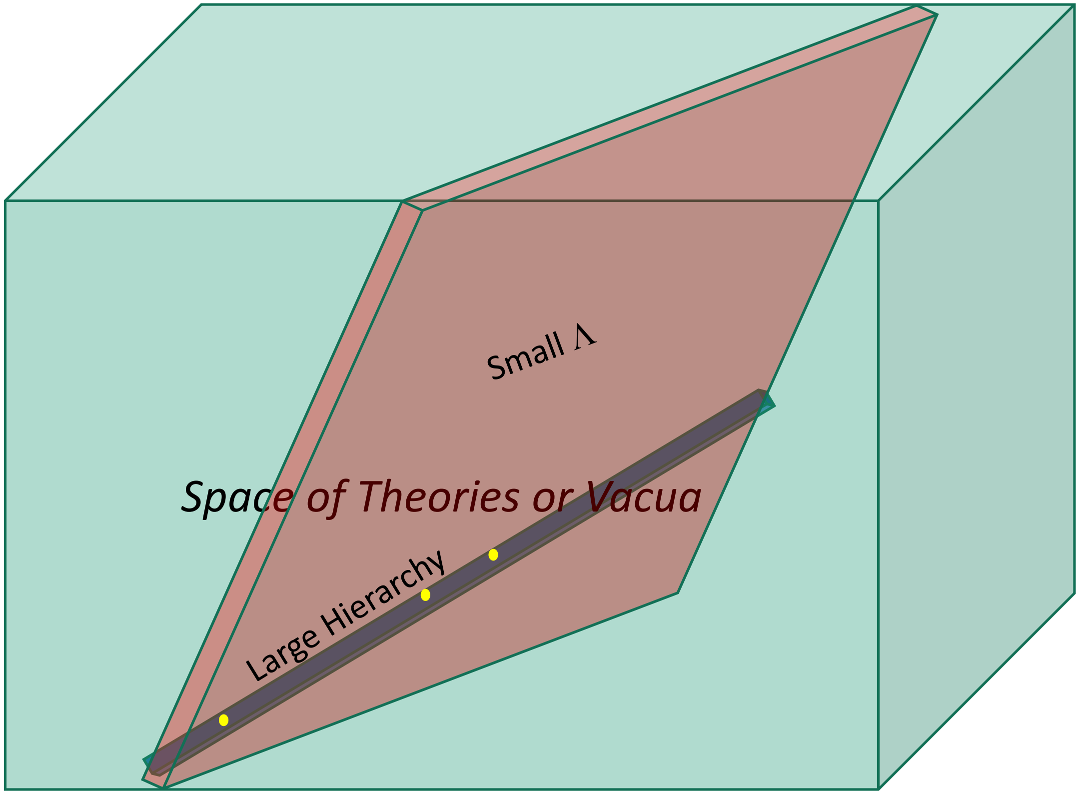
To apply the anthropic argument to the Higgs naturalness problem, need a third criterion!

What are X and X'?

How Has This Been Evaded?

Solutions to naturalness problem using anthropic arguments?

- They put in strong constraints on their original landscape
  - Only Standard Model fields (or MSSM fields)
  - Certain couplings (not all) allowed to vary widely



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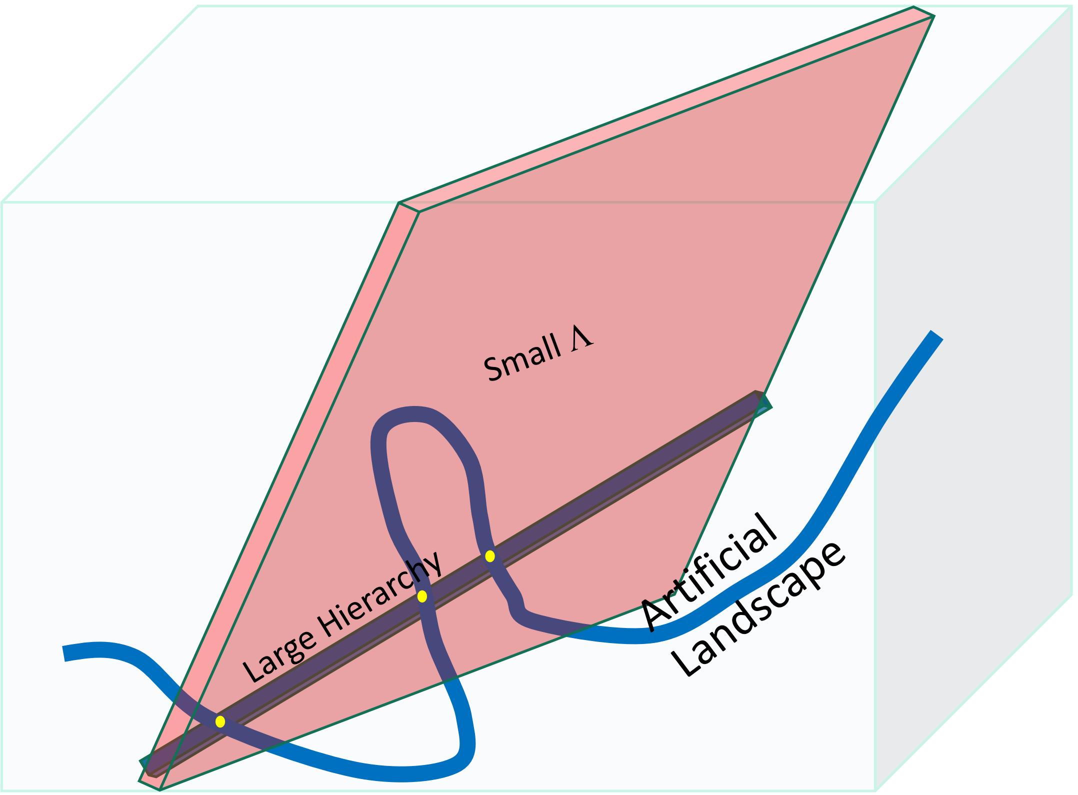
- Then yes, only path to mass hierarchy is a small Higgs vev.

… avoid "weakless" small-Yukawas large-vev solutions?

But not in a general landscape!

So if true, requires dynamical and/or fundamental explanation!



String Theory and Naturalness

String theory's landscape of 10^{XXX} vacua

- Ok for solving the cosmological constant problem and
- Ok for explaining why there is a hierarchy

- But without a 3rd criterion can't solve the Higgs-naturalness problem…

- *Unless you believe (or prove) something amazing about string vacua!*

- String theory seems to predict that observers will find themselves in a vacuum whose hierarchy is **natural**…

- If the unnatural SM continues to survive unscathed at the LHC, string theory will become increasingly implausible as a theory of nature

Non-anthropic historical solutions

- Relaxion
  - CC problem remains to be solved
  - Anthropics? Problem potentially reappears…
    - Why must nature choose a relaxion when it could choose technicolor?
    - Unless solving CC problem requires it… extremely baroque

Graham et al. '15

- Nnaturalness
  - Picks least natural sector
  - But artificial to make all sectors resemble SM
    - Reasonable for some sectors to be even less natural than the SM.

Arkani-Hamed et al. '16

- Name TBD - Stanford group
  - Link existence of hierarchy to solution of CC problem

Still a long way from a convincing historical example…

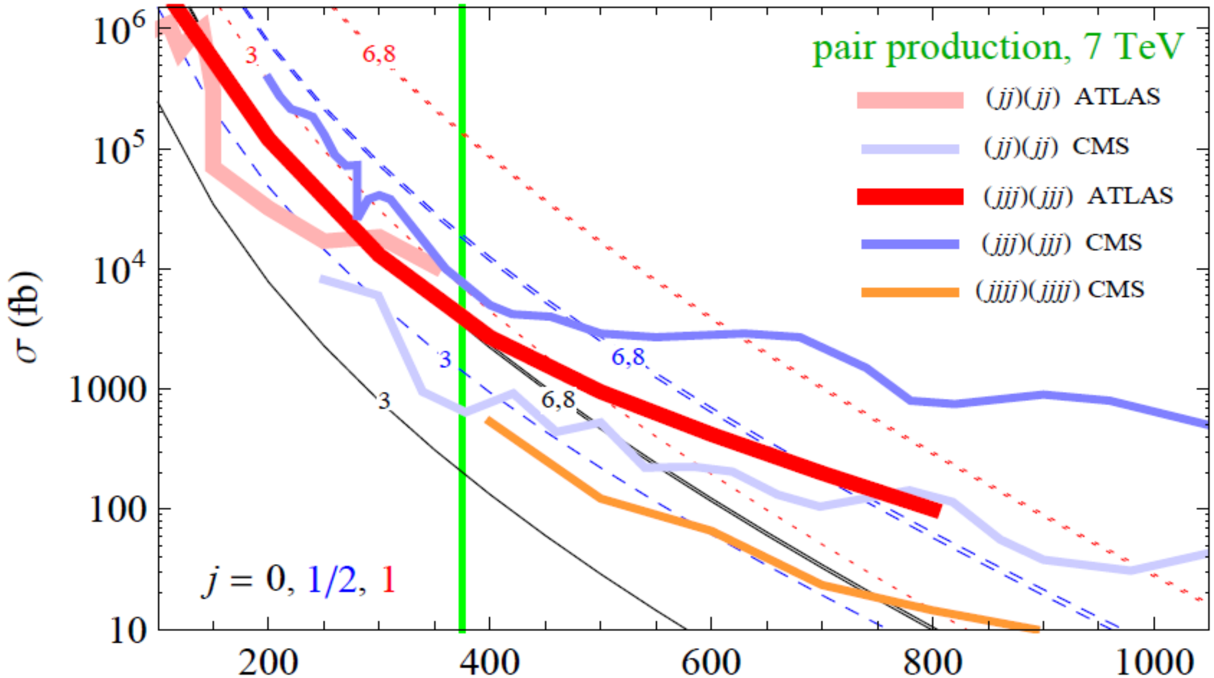
- But still early days

So we need to dig deep

- Digging Deep Topics
  - Buried treasure - resonances hiding in inclusive samples*
  - Tiny resonances from bound states^
  - Looking for tricky t’ and b’
  - Taking ratios of processes at 7/8 vs 13/14 TeV*
  - Diboson ratios as example of precision observables*^

*Presented in SEARCH2016 talk

^Discussed today



Mass of **Constituent** (GeV)

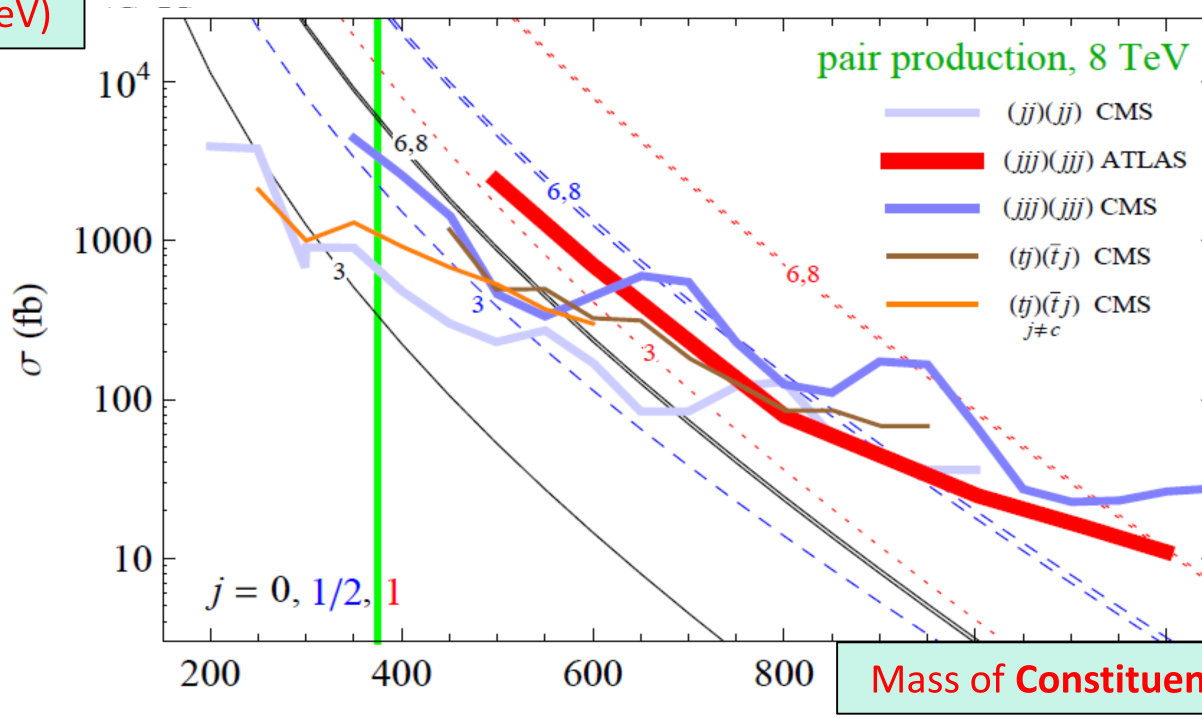
Direct Searches
at 7-8 TeV for
<u>constituent</u> particles
decaying to jets

Note! Not every representation can decay to every final state!

Spin 0 solid

Spin ½ dashed

Spin 1 dotted



Mass of **Constituent** (GeV)

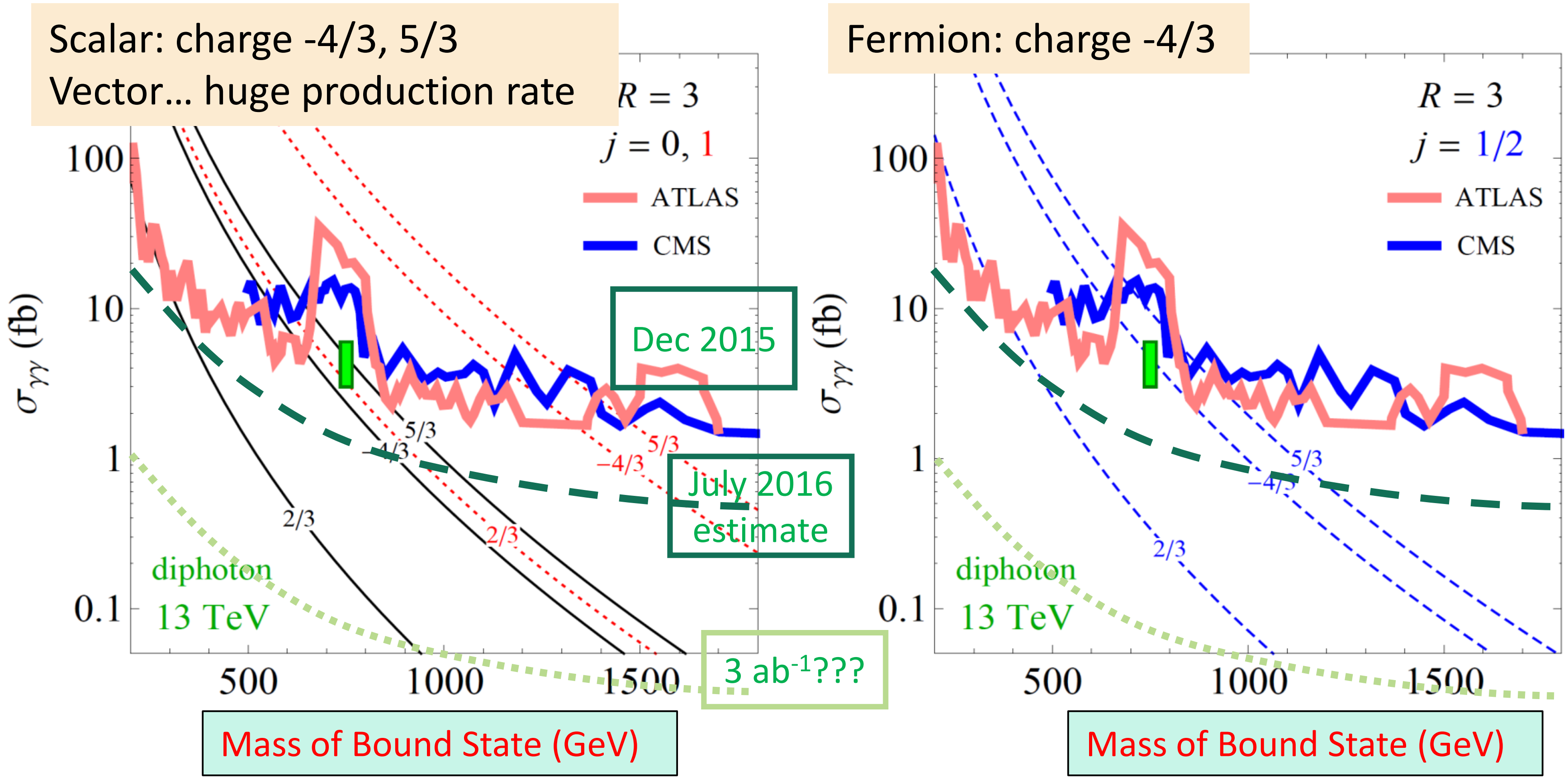
Kats & MJS '12, '16

So we need to dig deep

- No point in digging deep yet if we haven’t scratched the surface
  - Yes, we are now searching effectively for gluinos
    - And anything else with lots of color and/or spin
  - Need to check that we are searching effectively for triplet fermions (t’,b’)
  - Color triplet scalars – top squark is good target

- Colored particles with simple decays are easy to search for
- Colored particles with more complex decays
  - Are decaying to MET or leptons or photons, easy to find
  - Are decaying via known or unknown resonances, not too hard to find
  - Are decaying to multijets without intermediate resonances – miss?
    - But then likely decaying with a delay
    - Chance to observe their bound states
  - Are confined by another force: bound states

Diphoton Limits as of Dec. 2015



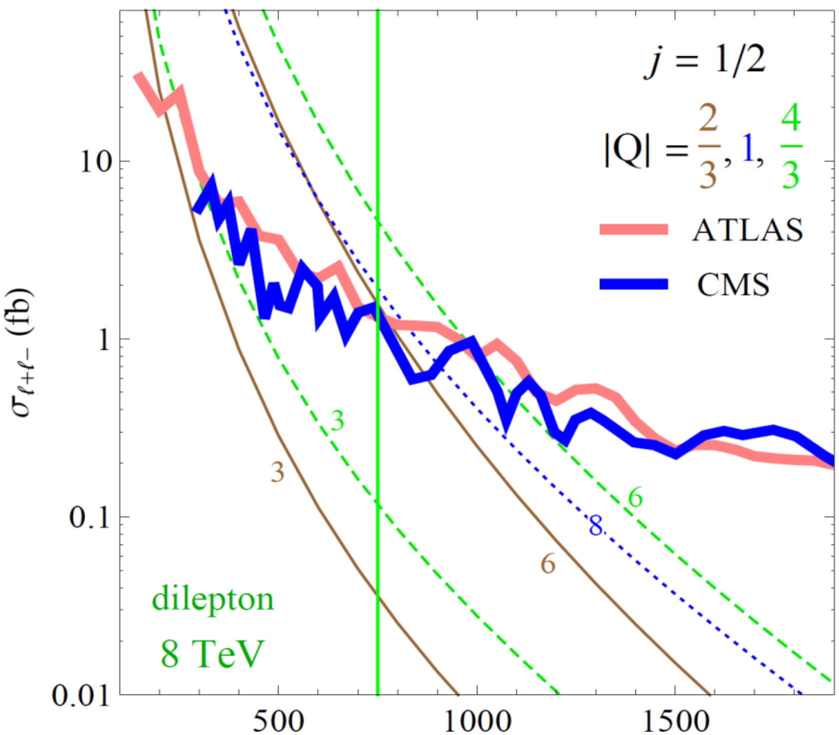
Guesstimate: Can rule out stabilized scalars and spinors with large charge up to at least 700-800 GeV, with Q=2/3 perhaps up to 500 GeV

Kats & MJS '12, '16

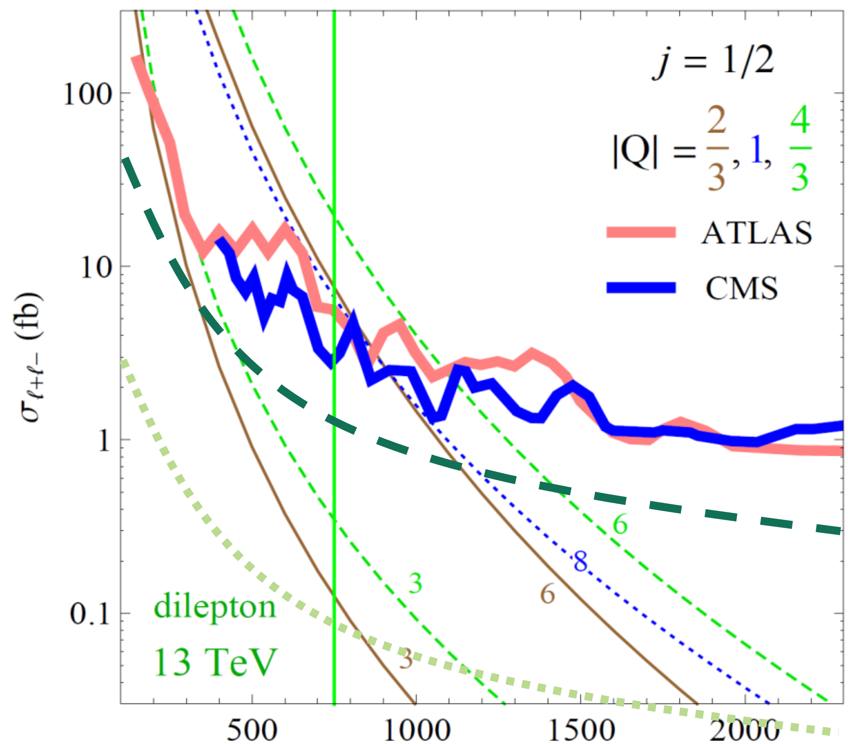
Dilepton Limits from 2015

Guesstimate: For fermions, dileptons similar to diphotons at Q=2/3, worse at higher Q

- For bound states of fermions only:



Mass of Bound State (GeV)



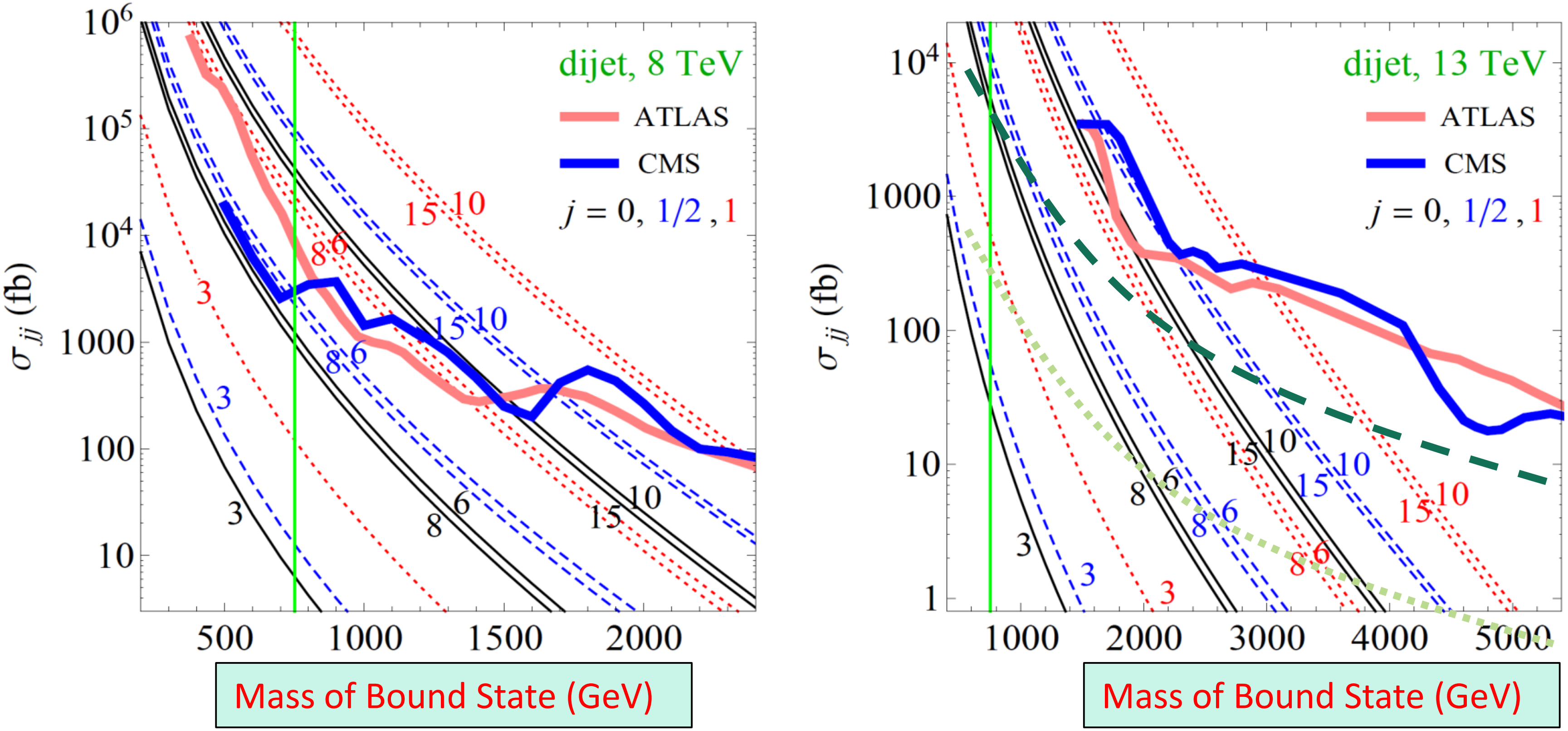
Mass of Bound State (GeV)

- To make dileptons with high rate, need spin-1 bound state
- This is s-wave for fermions but p-wave for scalars, suppressed rate

Kats & MJS '12, '16

Dijet Limits from 2015

- From singlet resonances



Kats & MJS ‘12, ‘16

Examples of Enhancements

If any of these particles was a (3,3) of $SU(3)xSU(3)_{twin}$,

- Even if no quirk-like confinement…

- Effective α doubles;
    - Bound state wave function $\Psi(0) \sim \alpha^{3/2}$
    - Total rate grows by 8
- And there are three of them, from QCD point of view

Even if SU(2)xU(1) neutral, dijets could exclude to few hundred GeV

Quirks/Squirks: greater enhancement

- 3 of them, from QCD point of view
- Total pair cross-section converted into resonant cross-section

Dibosons

with Chris Frye, Marat Freytsis, Jakub Scholtz '15

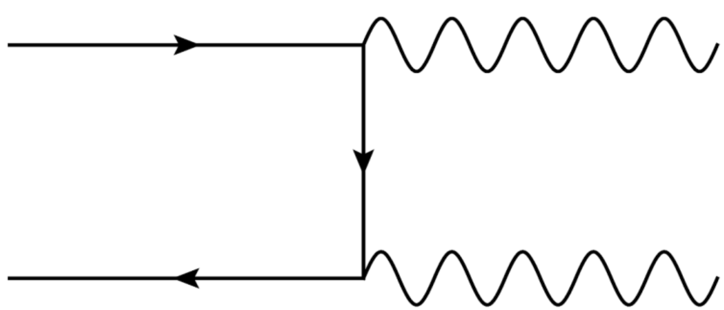
Production of any pair of photon, Z, $W^{\pm}$ (except same sign)

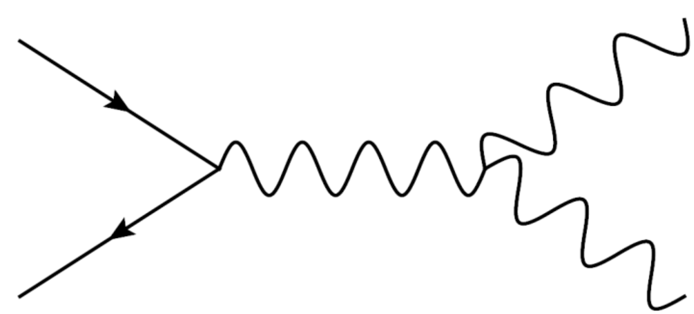
- Discrepancies have shown up – or not…
- What ratios/variables might help?

- Put high-energy $SU(2)xU(1)$ 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, Williams

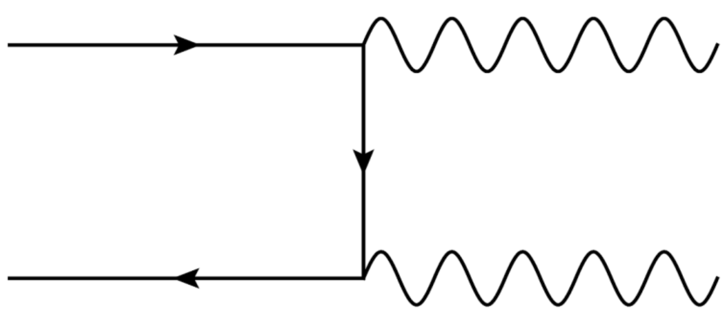


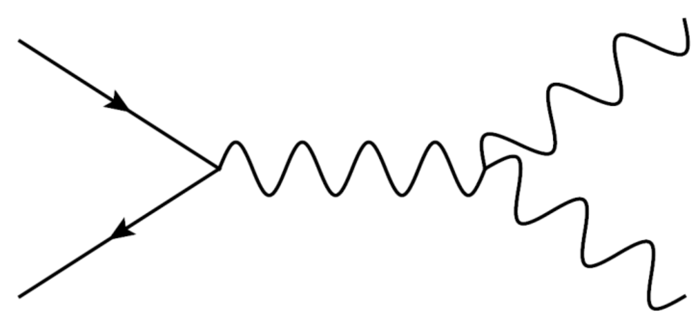


$SU(2)$ w^a (a=1,2,3), $U(1)$ x

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

$$\boxed{\begin{aligned}\gamma &= c_W\, x + s_W\, w^3\,,\\ Z &= c_W\, w^3 - s_W\, x\,,\end{aligned}}$$





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

t,u

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s,t,u

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

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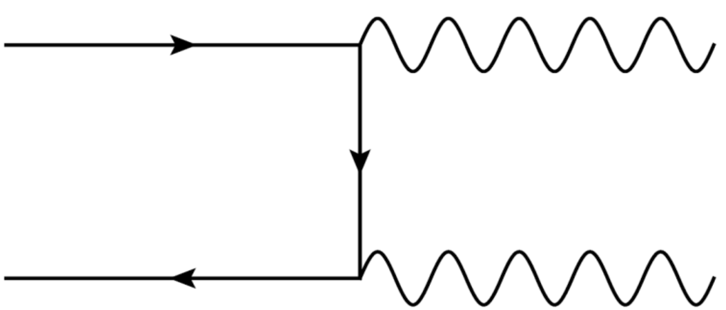

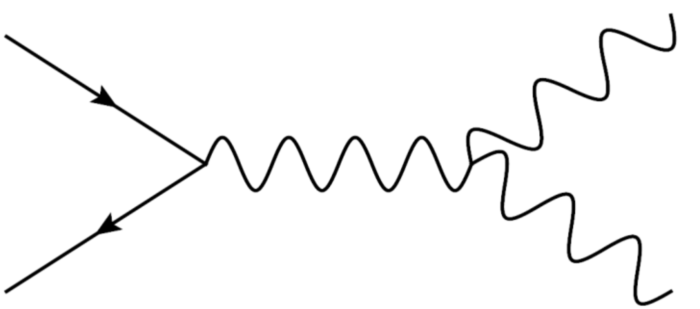

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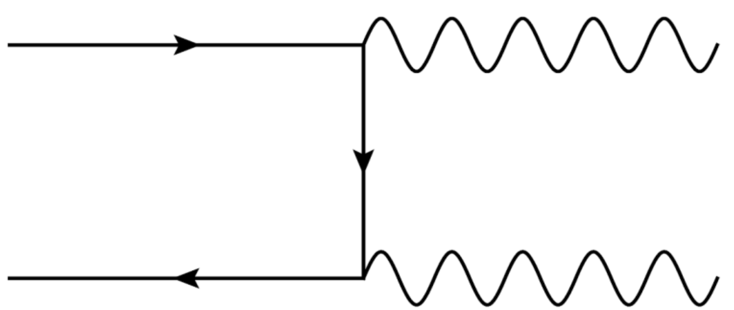

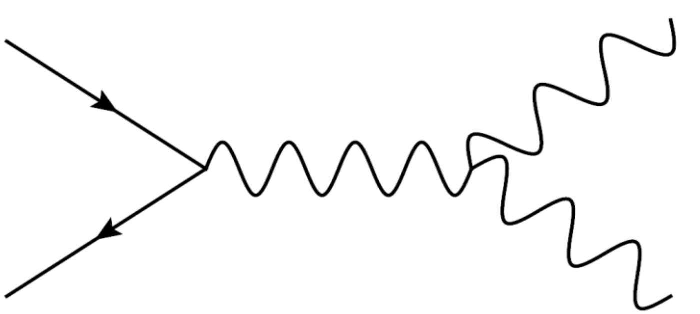

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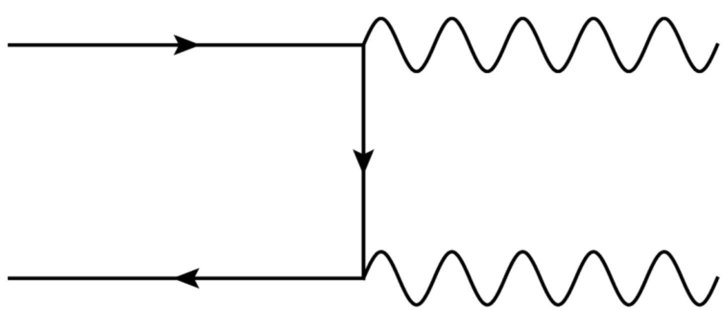

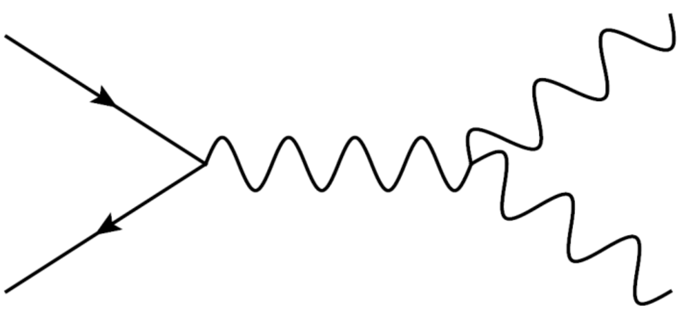

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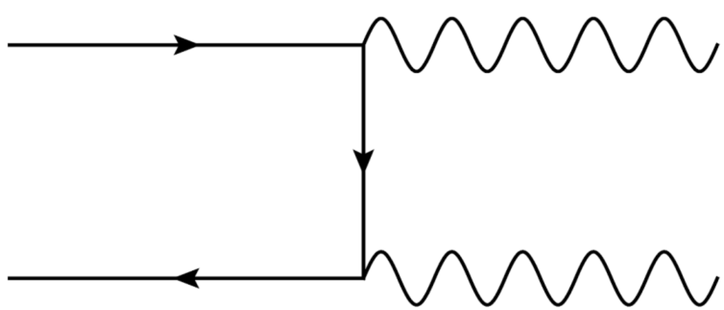

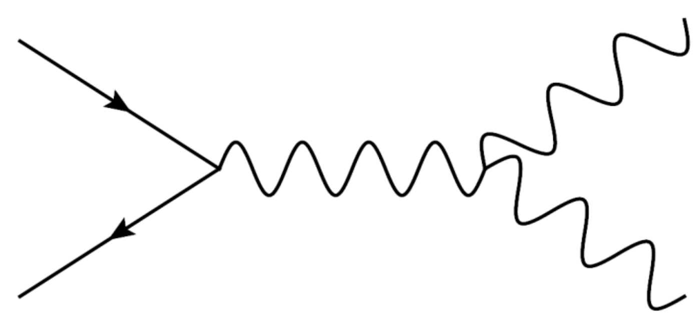

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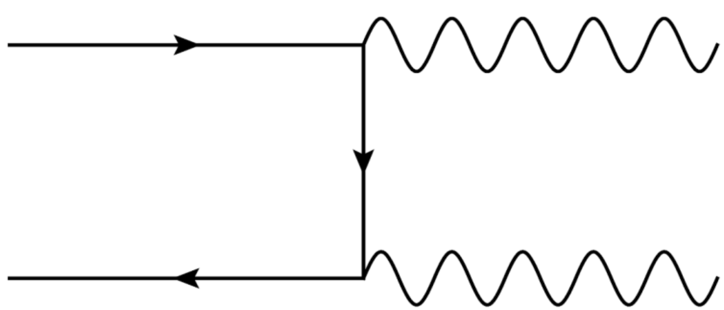

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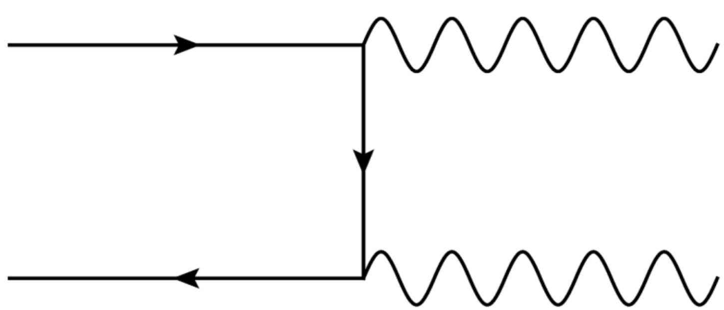
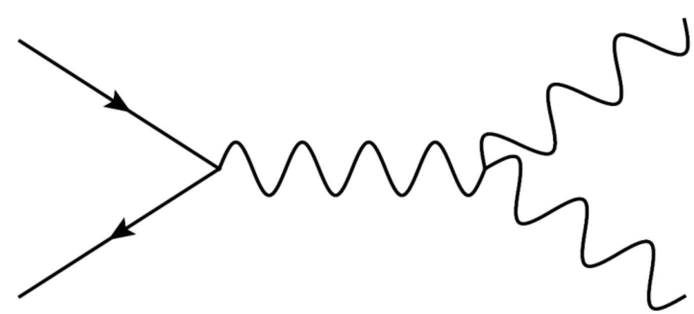
$$|a_\phi|^2 = \frac{\hat{t}\hat{u}}{4\,\hat{s}^2}\,.$$

a_3 vanishes at $t = u$ *(90^o)*

i.e. at threshold for fixed p_T

$$a_1(\hat{t},\hat{u}) = a_1(\hat{u},\hat{t}), \qquad a_3(\hat{t},\hat{u}) = -a_3(\hat{u},\hat{t}), \qquad |a_\phi(\hat{t},\hat{u})| = |a_\phi(\hat{u},\hat{t})|.$$





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

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

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

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

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

Couplings to Z :

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

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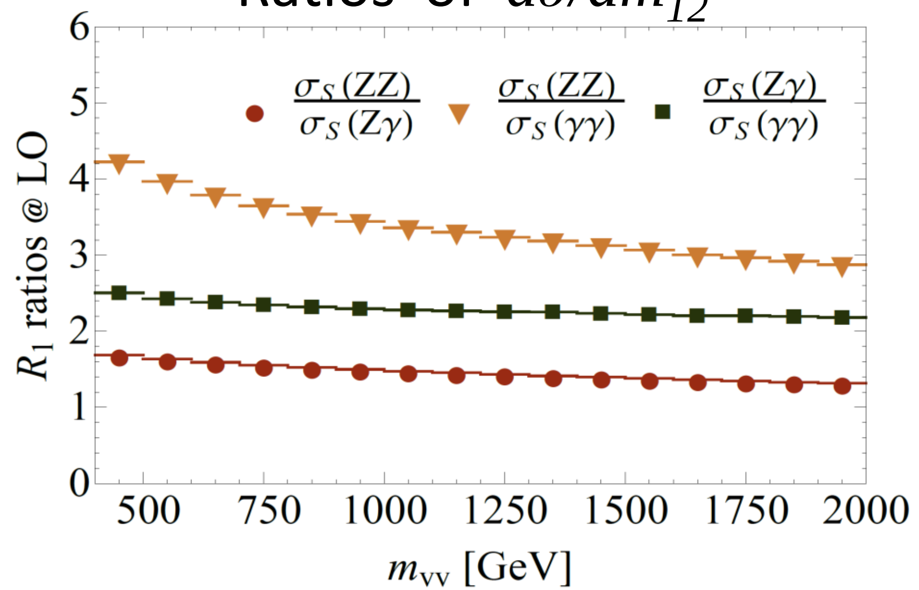
$$C_{ZZ}^q = \frac{1}{2}\,\frac{\pi\alpha_2^2 c_W^4}{N_c}\,\left(L^4 + R^4\right) .$$

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

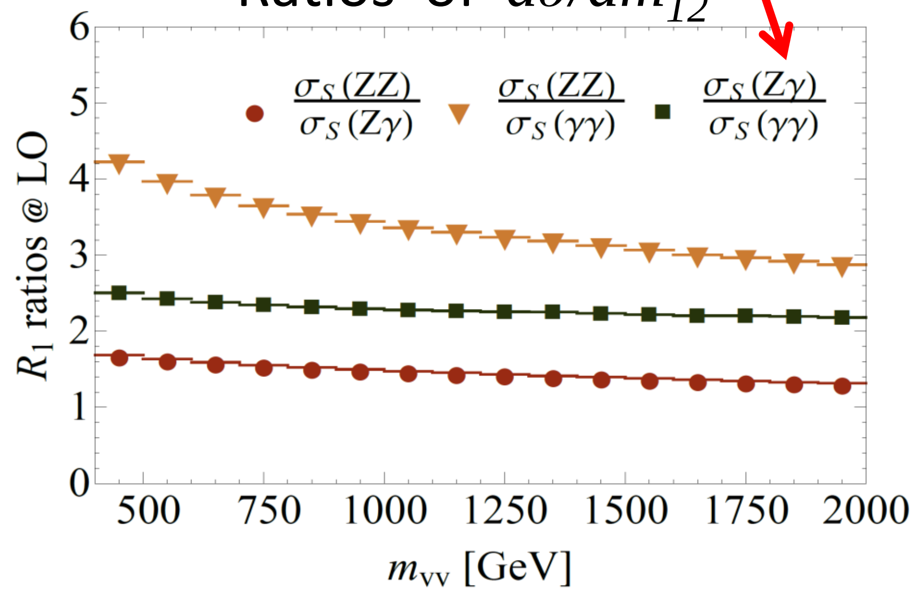
$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q} \to V_1^0 V_2^0) = \frac{C_{12}^q}{\hat{s}^2} |a_1|^2 ,$$

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

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

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

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



Couplings to Z :

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

Processes with $W^{\pm}$

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q}' \to W^{\pm}\gamma) = \frac{\pi |V_{ud}|^2 \alpha_2^2 s_W^2}{N_c\, \hat{s}^2} \left[\frac{Y_L^2}{2} |a_1|^2 \pm 2 Y_L (a_1 a_3) + 4 |a_3|^2 \right]$$

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q}' \to W^{\pm}Z) = \frac{\pi |V_{ud}|^2 \alpha_2^2}{N_c\, \hat{s}^2} \left[\frac{s_W^2 t_W^2 Y_L^2}{2} |a_1|^2 \mp 2 s_W^2 Y_L (a_1 a_3) + 4 c_W^2 |a_3|^2 + \frac{1}{2} |a_\phi|^2 \right]$$

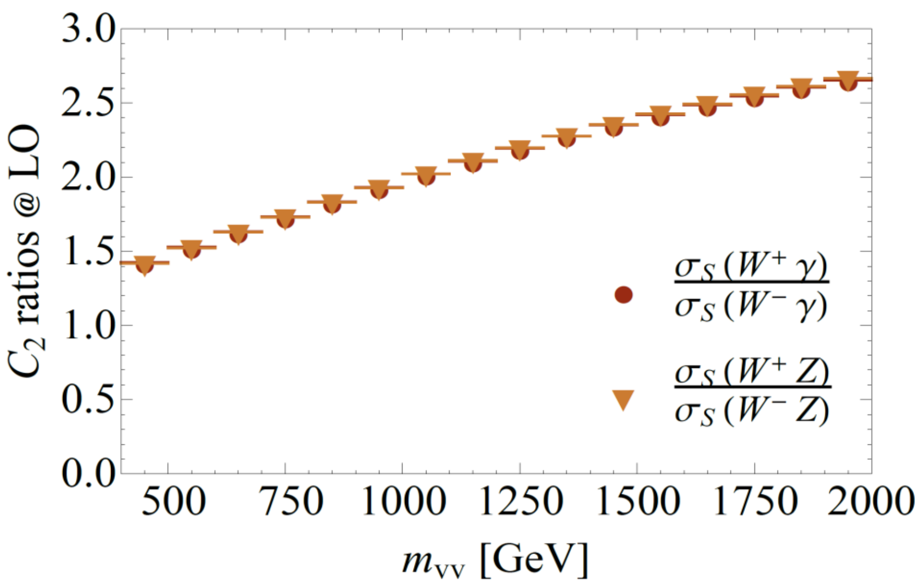
$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q} \to W^- W^+) = \frac{\pi\, \alpha_2^2}{N_c\, \hat{s}^2} \left\{ \frac{1}{16} |a_1|^2 \pm \frac{1}{2} (a_1 a_3) + 2 |a_3|^2 \right.$$

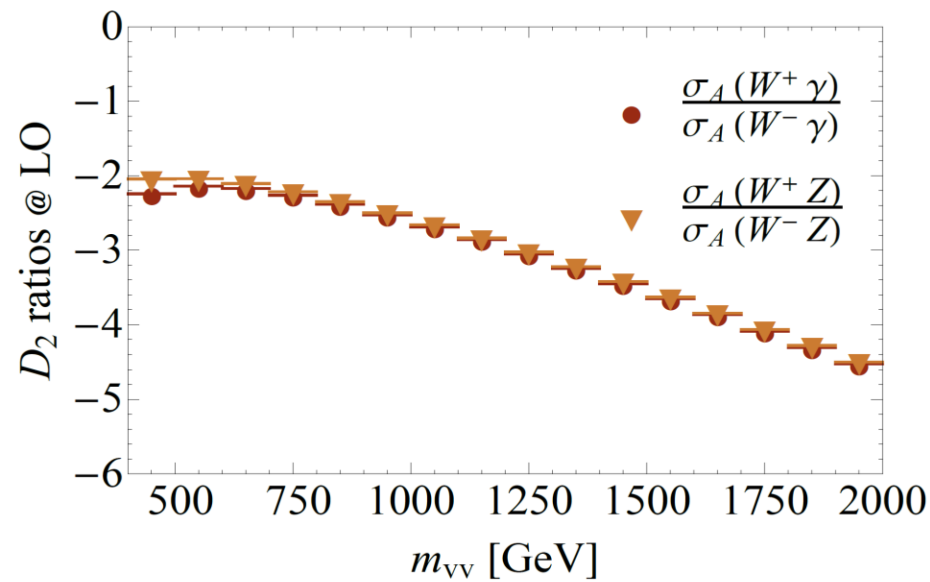
$$\left. + \left[(t_W^2\, Y_R)^2 + (t_W^2\, Y_L + T_3)^2 \right] |a_\phi|^2 \right\}$$

Upper signs for *q=u*
Lower signs for *q=d*

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

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





Processes with $W^{\pm}$

Some Terms Are Small (Y_L , s_W , a_φ)

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q}' \to W^{\pm}\gamma) = \frac{\pi |V_{ud}|^2 \alpha_2^2 s_W^2}{N_c\, \hat{s}^2} \left[\cancel{\frac{Y_L^2}{2}|a_1|^2} \pm \cancel{2Y_L(a_1 a_3)} + 4|a_3|^2 \right]$$

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q}' \to W^{\pm}Z) = \frac{\pi |V_{ud}|^2 \alpha_2^2}{N_c\, \hat{s}^2} \left[\cancel{\frac{s_W^2 t_W^2 Y_L^2}{2}|a_1|^2} \mp \cancel{2s_W^2 Y_L(a_1 a_3)} + 4c_W^2 |a_3|^2 + \cancel{\frac{1}{2}|a_\phi|^2} \right]$$

Upper signs for *q=u*
Lower signs for *q=d*

Processes with $W^{\pm}$

Some Terms Are Small (Y_L , s_W , a_φ)

But a_3 has a radiation zero!

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q}' \to W^{\pm}\gamma) = \frac{\pi |V_{ud}|^2 \alpha_2^2 s_W^2}{N_c\, \hat{s}^2} \left[\cancel{\frac{Y_L^2}{2}} |a_1|^2 \pm \cancel{2Y_L(a_1 a_3)} + \cancel{4|a_3|^2} \right]$$

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q}' \to W^{\pm}Z) = \frac{\pi |V_{ud}|^2 \alpha_2^2}{N_c\, \hat{s}^2} \left[\cancel{\frac{s_W^2 t_W^2 Y_L^2}{2}} |a_1|^2 \mp \cancel{2s_W^2 Y_L(a_1 a_3)} + \cancel{4c_W^2 |a_3|^2} + \cancel{\frac{1}{2}|a_\phi|^2} \right]$$

Upper signs for $q=u$
Lower signs for $q=d$

Processes with $W^{\pm}$

Some Terms Are Small (Y_L, s_W , a_φ)

But a_3 has a radiation zero!

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q}' \to W^{\pm}\gamma) = \frac{\pi |V_{ud}|^2 \alpha_2^2 s_W^2}{N_c\, \hat{s}^2} \left[\cancel{\frac{Y_L^2}{2}} |a_1|^2 \pm \cancel{2Y_L(a_1 a_3)} + 4|a_3|^2 \right]$$

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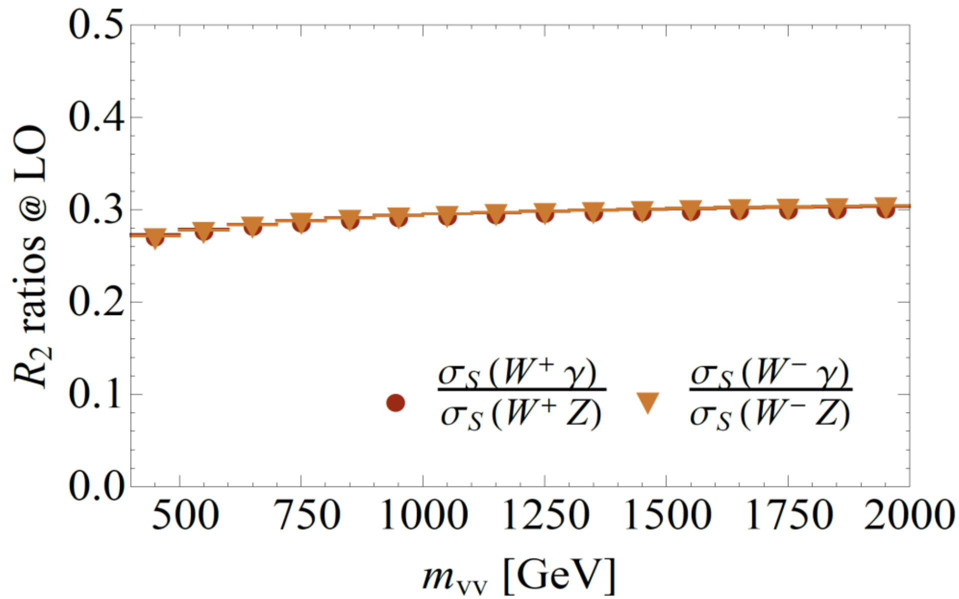
Away from threshold, $W\gamma$ / $WZ \sim \tan^2 \theta_W \sim .29$

Upper signs for $q=u$
Lower signs for $q=d$

Processes with $W^\pm$



Some Terms Are Small (Y_L, s_W,

But a_3 has a radiation zero!

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q}' \to W^\pm\gamma) = \frac{\pi |V_{ud}|^2 \alpha_2^2 s_W^2}{N_c\, \hat{s}^2}\left[\frac{Y_L^2}{2}|a_1|^2 \pm 2Y_L\cancel{(a_1 a_3)} + \cancel{4|a_3|^2}\right]$$

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q}' \to W^\pm Z) = \frac{\pi |V_{ud}|^2 \alpha_2^2}{N_c\, \hat{s}^2}\left[\frac{s_W^2 t_W^2 Y_L^2}{2}|a_1|^2 \mp 2s_W^2 \cancel{Y_L(a_1 a_3)} + 4\cancel{c_W^2|a_3|^2} + \frac{1}{2}|a_\phi|^2\right]$$

Away from threshold, $W\gamma$ / $WZ \sim \tan^2\theta_W \sim .29$

At (but only very close to) threshold, $W\gamma$ / $WZ \sim .19$

Upper signs for $q=u$
Lower signs for $q=d$

Processes with $W^\pm$

Some Terms Are Small (Y_L , s_W , a_φ)

But a_3 has a radiation zero!

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

for FB-symmetric quantities, WW is related to $\gamma\gamma$

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q}' \to W^\pm\gamma) = \frac{\pi|V_{ud}|^2\alpha_2^2 s_W^2}{N_c\,\hat{s}^2}\left[\cancel{\frac{Y_L^2}{2}}|a_1|^2 \pm \cancel{2Y_L(a_1a_3)} + \cancel{4|a_3|^2}\right]$$

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q}' \to W^\pm Z) = \frac{\pi|V_{ud}|^2\alpha_2^2}{N_c\,\hat{s}^2}\left[\cancel{\frac{s_W^2 t_W^2 Y_L^2}{2}}|a_1|^2 \mp \cancel{2s_W^2 Y_L(a_1a_3)} + \cancel{4c_W^2|a_3|^2} + \cancel{\frac{1}{2}|a_\phi|^2}\right]$$

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q} \to W^- W^+) = \frac{\pi\,\alpha_2^2}{N_c\,\hat{s}^2}\left\{\frac{1}{16}|a_1|^2 \pm \cancel{\frac{1}{2}(a_1a_3)} + \cancel{2|a_3|^2} + \cancel{\left[(t_W^2 Y_R)^2 + (t_W^2 Y_L + T_3)^2\right]|a_\phi|^2}\right\}$$

Upper signs for *q*=*u*
Lower signs for *q*=*d*

Processes with $W^{\pm}$

Some Terms Are Small (Y_L , s_W , a_φ)

But a_3 has a radiation zero!

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

for FB-symmetric quantities, WW is related to $\gamma\gamma$

for FB-antisym quantities, WW is related to $W\gamma$ (WZ too small)

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q}' \to W^{\pm}\gamma) = \frac{\pi|V_{ud}|^2\alpha_2^2 s_W^2}{N_c\,\hat{s}^2}\left[\cancel{\frac{Y_L^2}{2}}|a_1|^2 \pm \cancel{2Y_L(a_1a_3)} + \cancel{4|a_3|^2}\right]$$

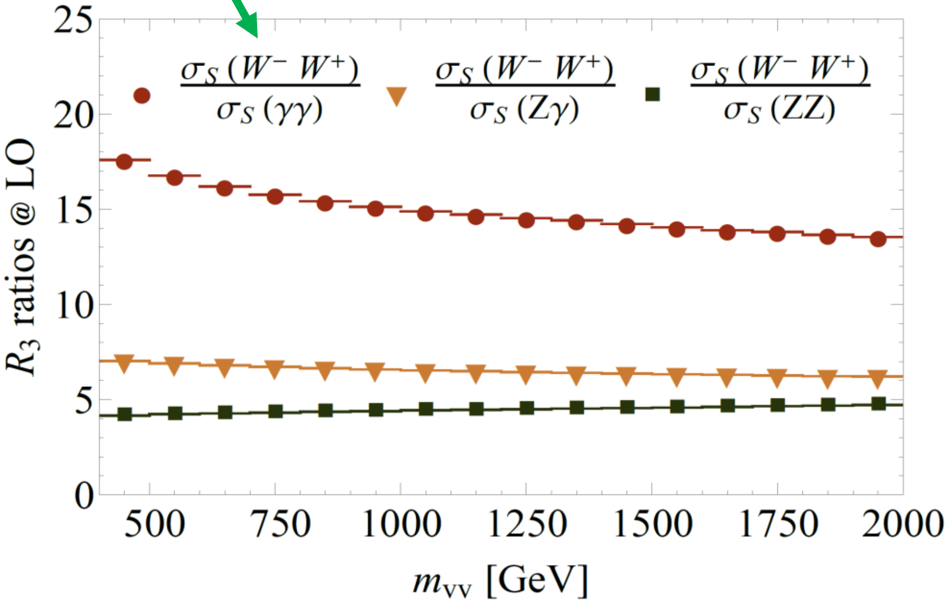
$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q}' \to W^{\pm}Z) = \frac{\pi|V_{ud}|^2\alpha_2^2}{N_c\,\hat{s}^2}\left[\cancel{\frac{s_W^2 t_W^2 Y_L^2}{2}}|a_1|^2 \mp \cancel{2s_W^2 Y_L(a_1a_3)} + \cancel{4c_W^2|a_3|^2} + \cancel{\frac{1}{2}|a_\phi|^2}\right]$$

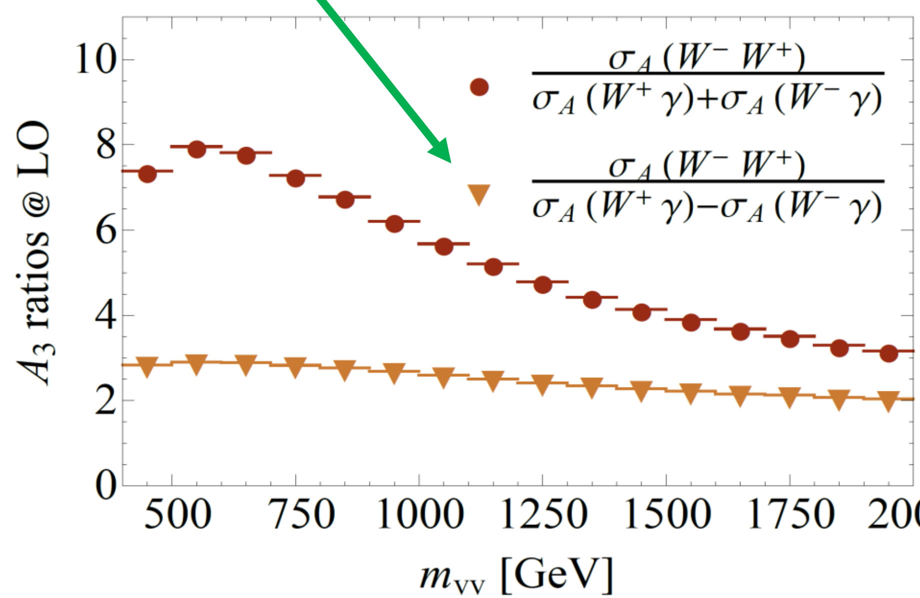
$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q} \to W^{-}W^{+}) = \frac{\pi\,\alpha_2^2}{N_c\,\hat{s}^2}\left\{\frac{1}{16}|a_1|^2 \pm \cancel{\frac{1}{2}(a_1a_3)} + \cancel{2|a_3|^2} + \cancel{\left[(t_W^2 Y_R)^2 + (t_W^2 Y_L + T_3)^2\right]|a_\phi|^2}\right\}$$

Upper signs for $q=u$
Lower signs for $q=d$

Best statistics

Best statistics and LO PDF behavior





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

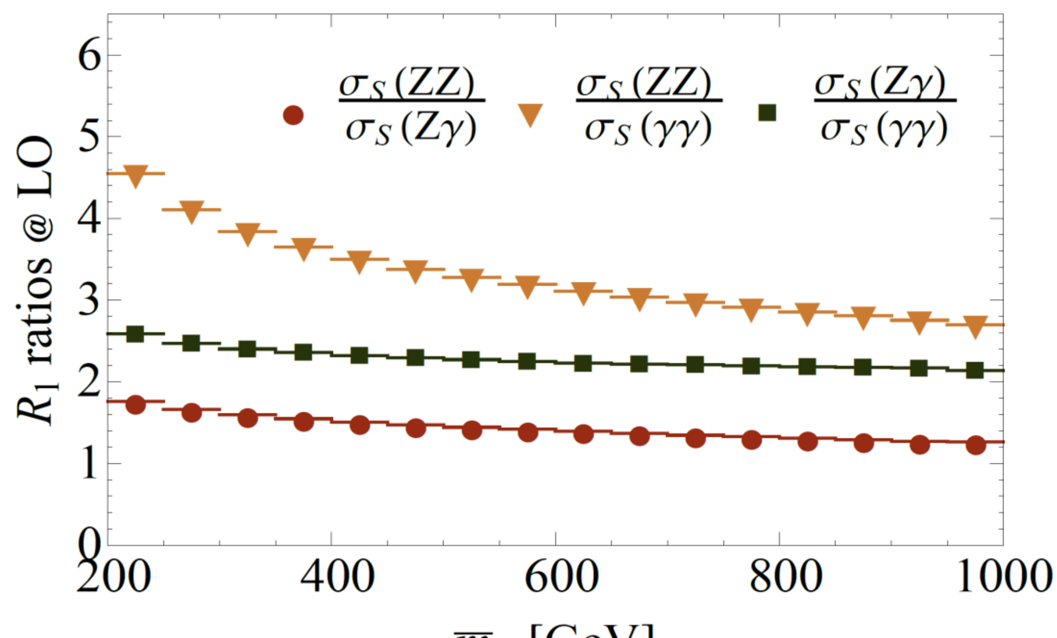
ZZ, $Z\gamma$, $\gamma\gamma$ at LO ➔ NLO

- 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

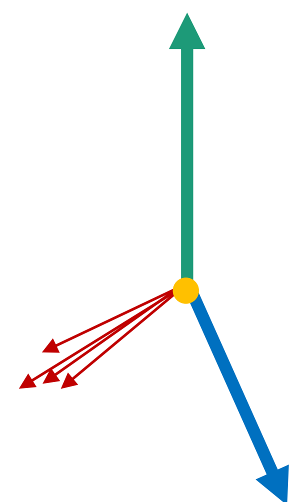
- Need to choose cuts carefully to avoid large NLO corrections
  - Assure cuts select kinematics similar to LO
    - i.e. no vector bosons softer than jets (cf. giant K factors)
  - But do not impose drastic jet veto

- We take

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

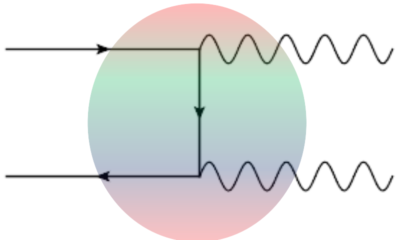
Notice these cuts scale –

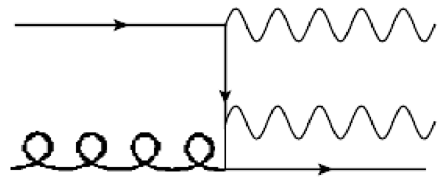
no large logs at high E



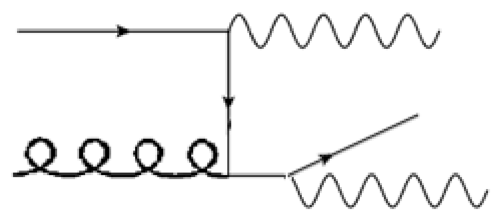
ZZ, $Z\gamma$, $\gamma\gamma$ at LO ➔ NLO

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

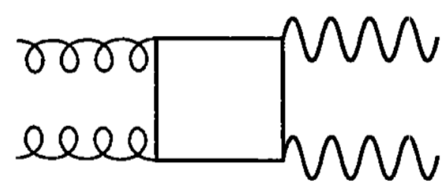




- …except…
  - Collinear quark-boson regime
    - Photon has log enhancement
    - Z has no enhancement

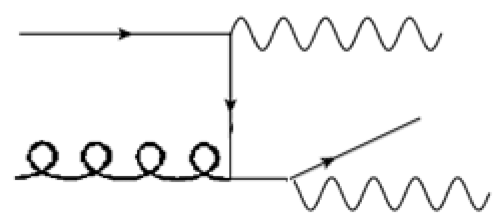


  - Gluon fusion process (formally NNLO but numerically large)

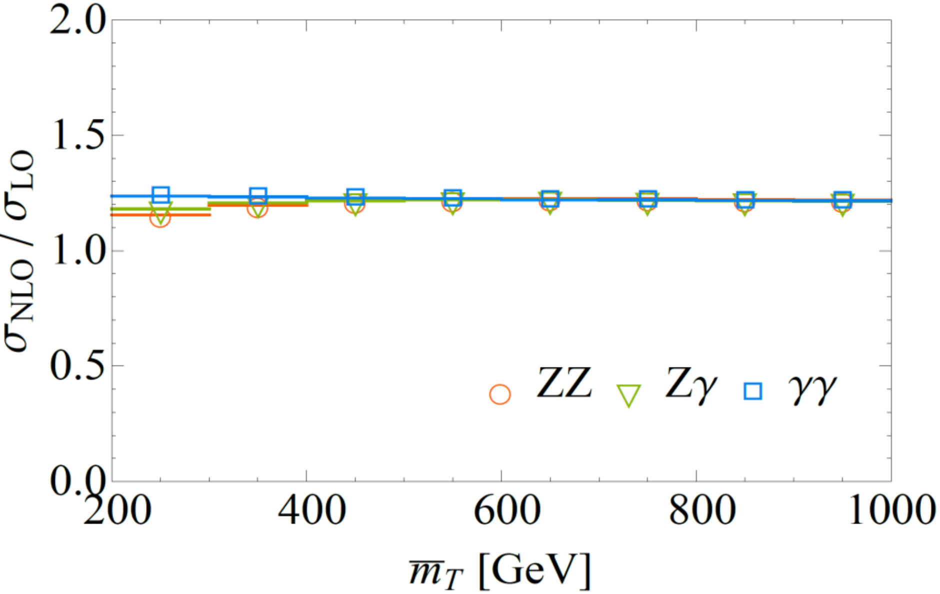


- Both of these driven by gluon pdf
  - Both decrease in importance at high energy

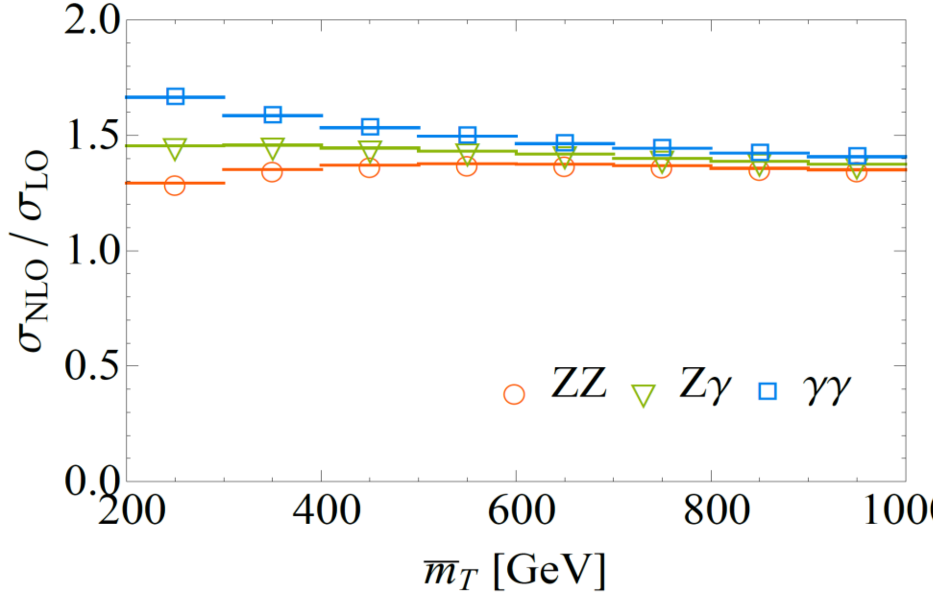
NLO/LO K factors



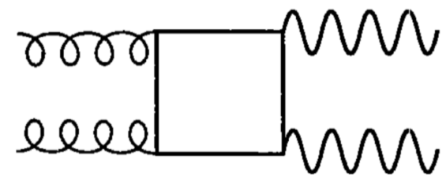
Collinear region cut away



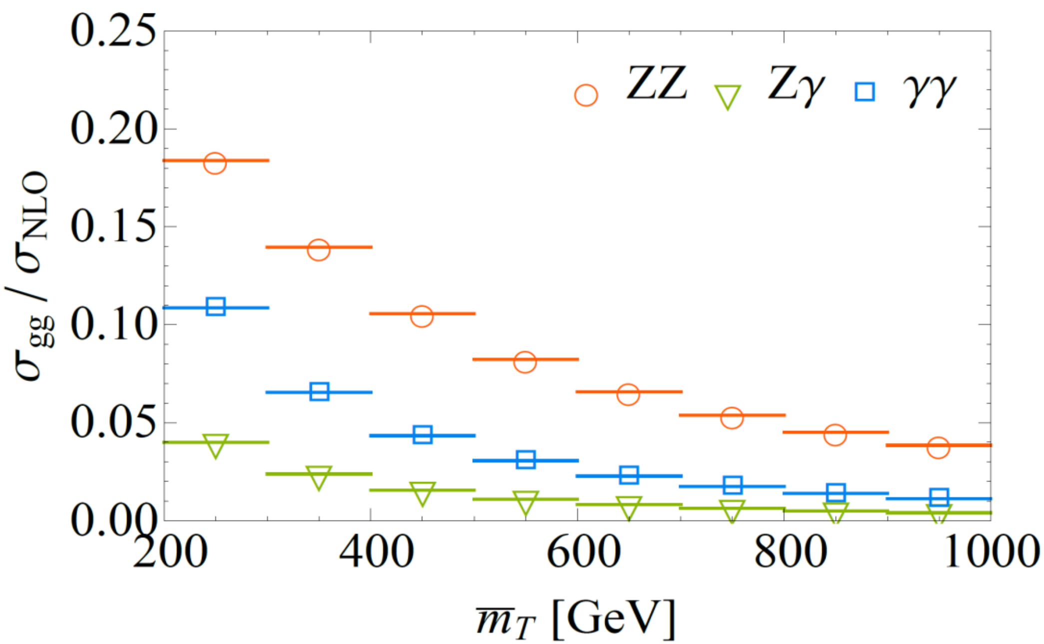
Collinear region included



NNLO gg / NLO partial K factor

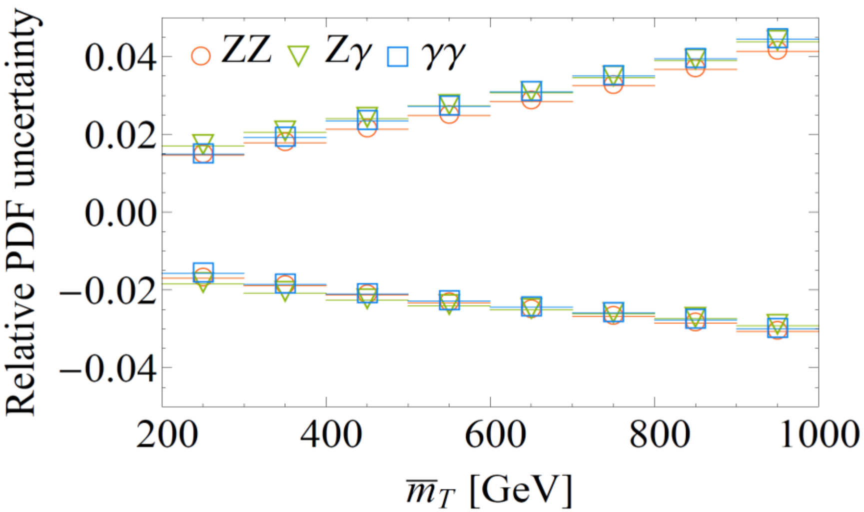


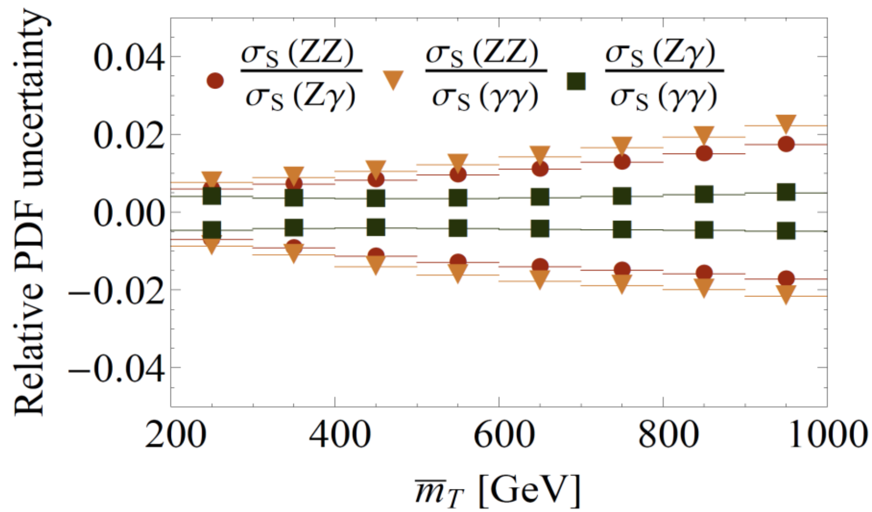
gg gives largest NNLO correction to ratios



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

PDF Uncertainties

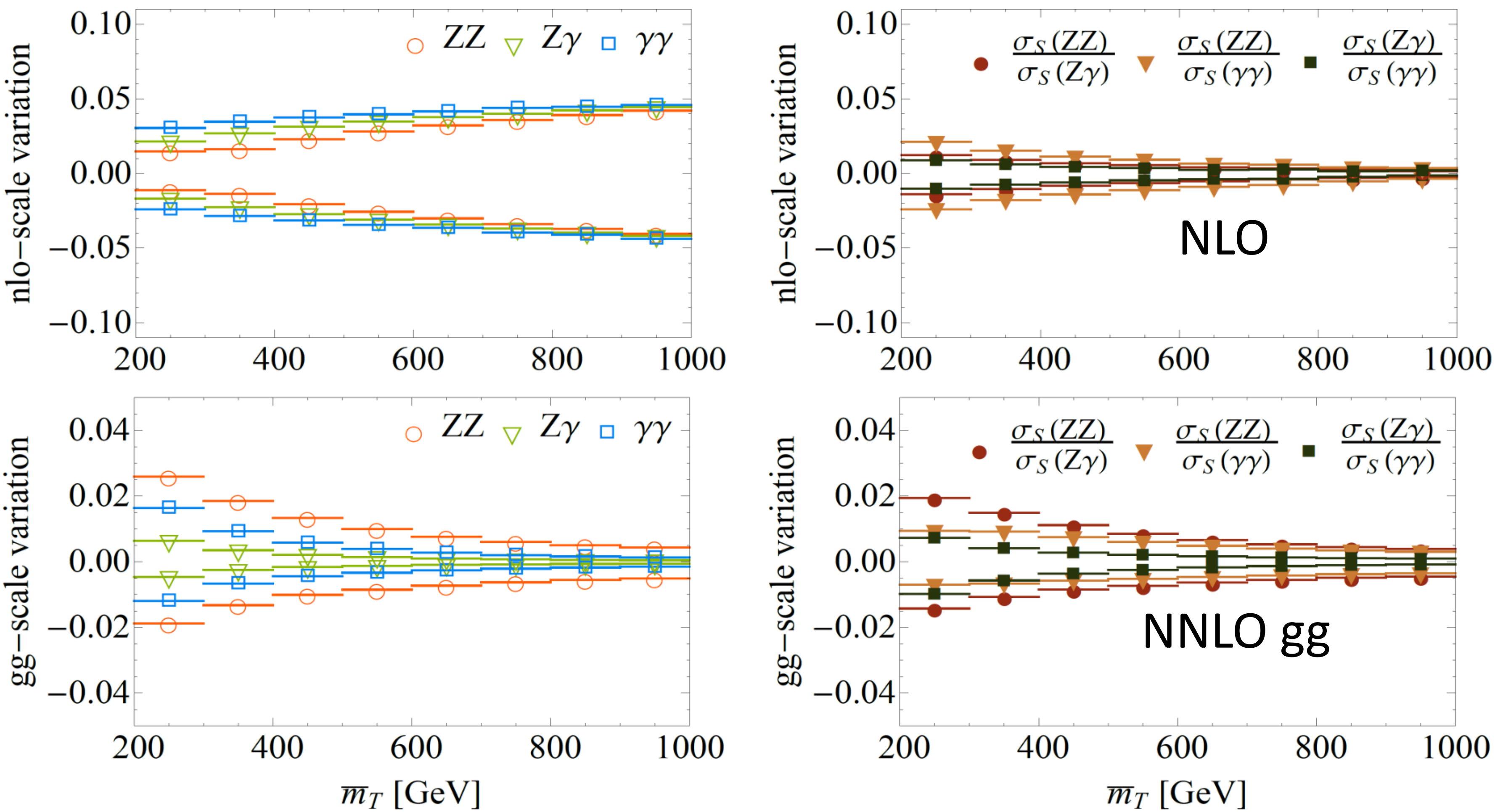




- Much smaller in ratios
  - 1 – 2 %

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%)

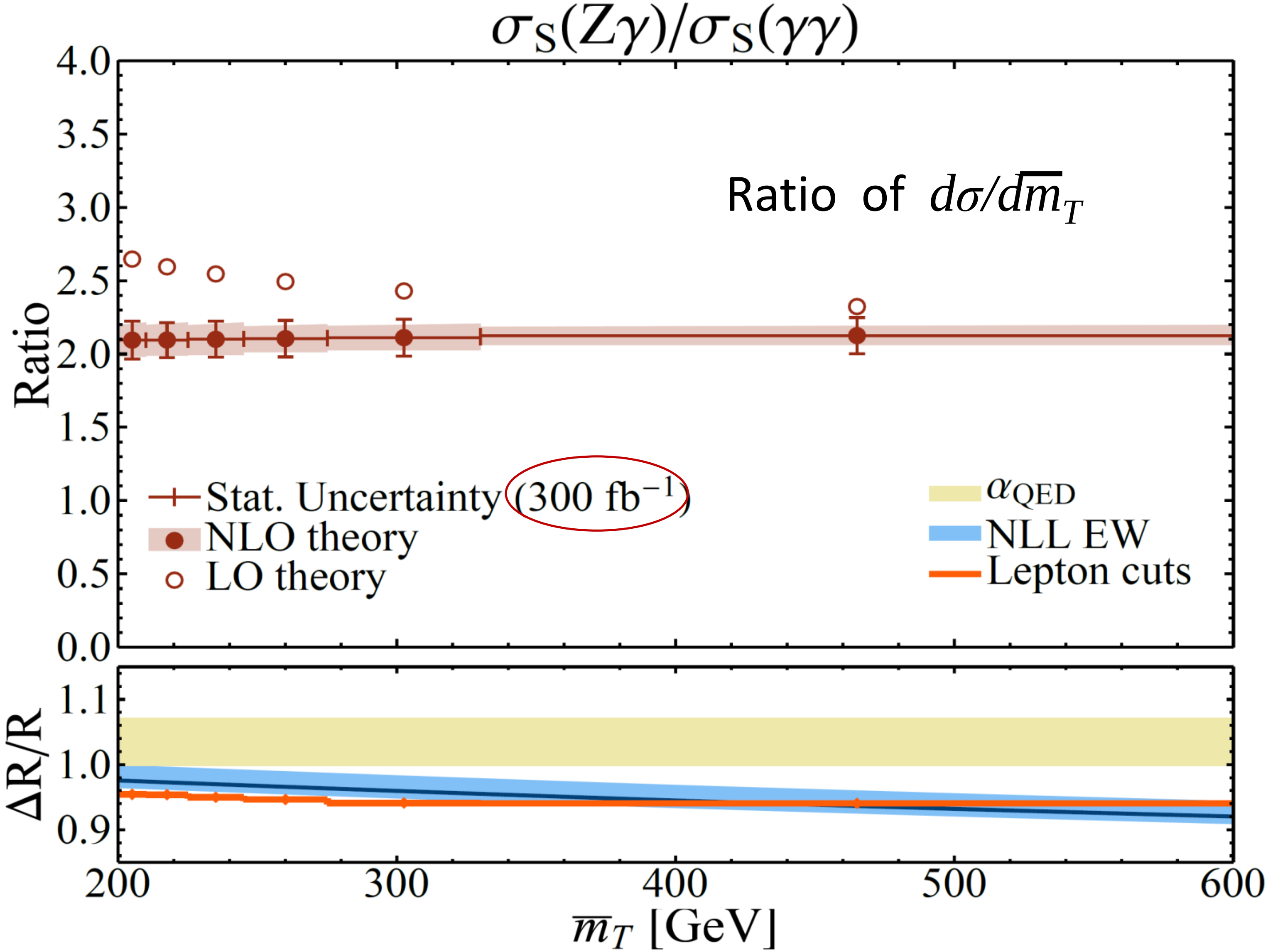
Experimental effects

- Some experimental issues cancel
  - Luminosity
  - Jet energy scale

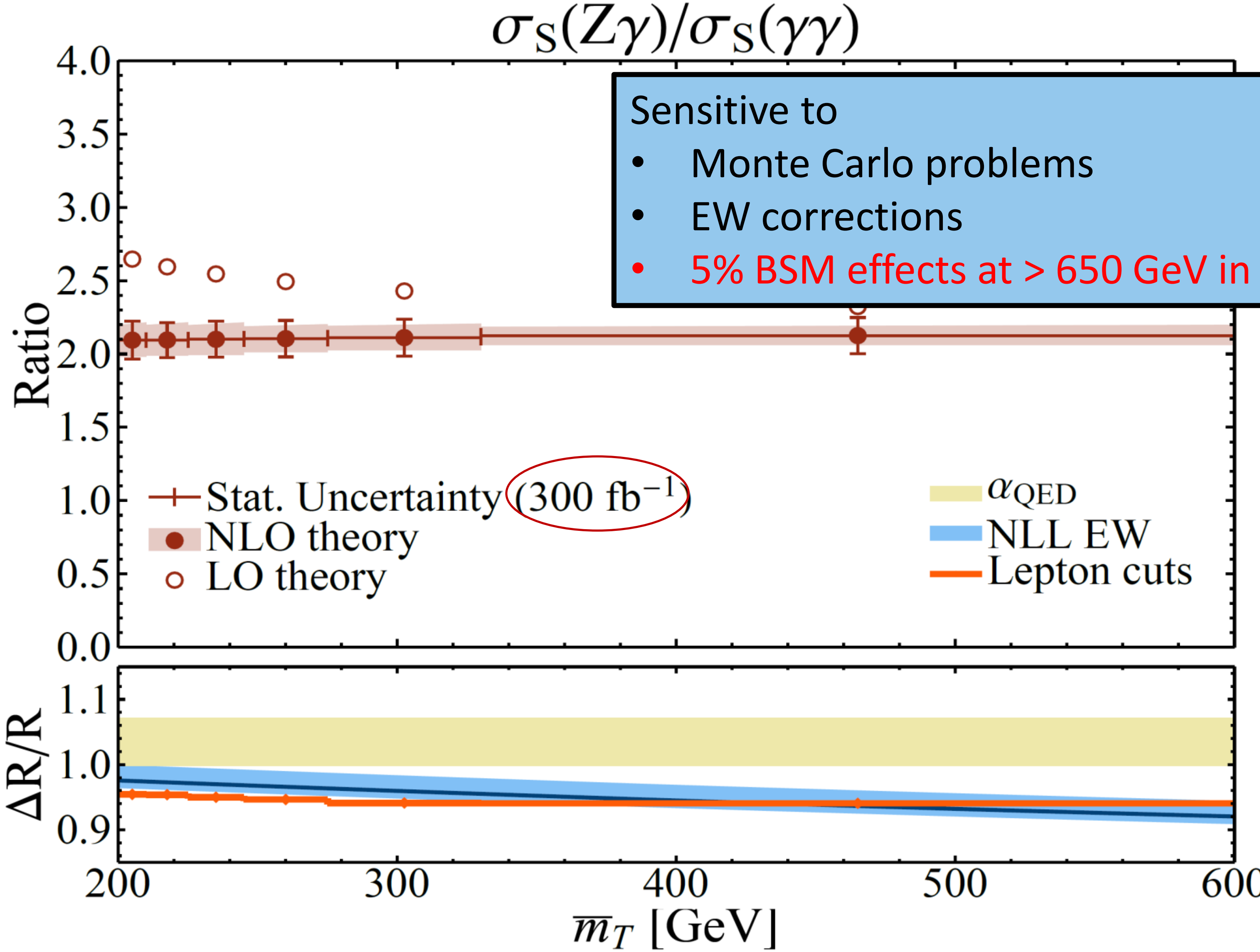
- Some don't:
  - Z → leptons – leptons have their own cuts, acceptance
      - Or → neutrinos -- other issues
    - Can be a substantial effect at low pT
    - But can model, measure with low absolute uncertainty
  - Z – finite width [experimental definition of "Z"]
    - Not large effect
    - Can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

Uncertainty budget

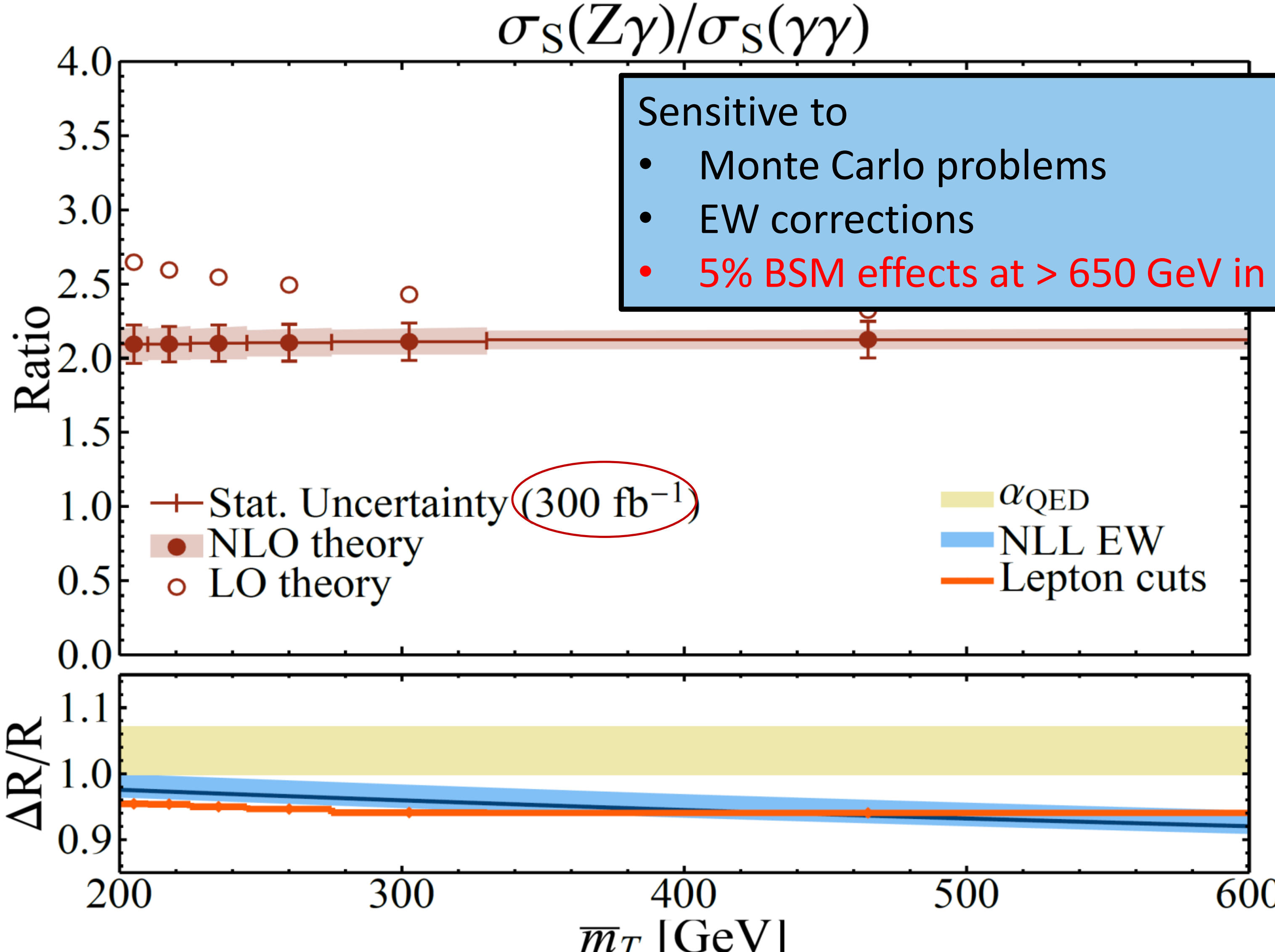
Effect	R_{1a} $(Z\gamma/\gamma\gamma)$	R_{1b} $(ZZ/\gamma\gamma)$	R_{1c} $(ZZ/Z\gamma)$	Comments
$qq \to VVqq$	2–3%	3–3.5%	1.5–2.5%	extrapolating $p^j_{T,\min} \to 0$ (Sec. 4.2)
μ_R, μ_F (gg)	0.5–1%	1%	1–2%	uses NLO $gg \to \gamma\gamma$ (Sec. 4.5)
μ_R, μ_F (NLO)	0.5–1%	1.5–2.5%	1–1.5%	varied independently (Sec. 4.5)
PDF	0.5%	1–1.5%	0.5–1%	MSTW 2008 using MCFM (Sec. 4.5)
α_{QED}	7%	14%	7%	Fully correlated (Sec. 4.4.2)
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
Stat. Uncertainty (300 fb^{-1})
NLO theory
LO theory
α_{QED}
NLL EW
Lepton cuts
$\Delta R/R$
$\overline{m}_T$ [GeV]



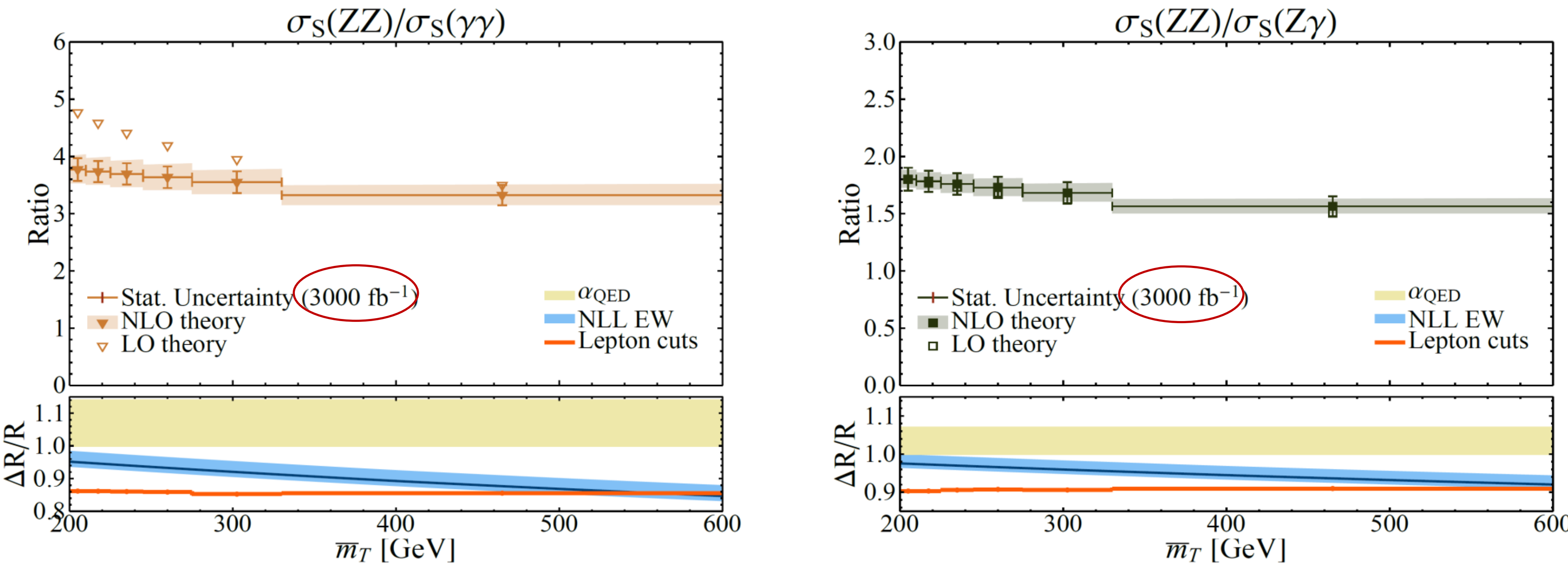
Sensitive to
- Monte Carlo problems
- EW corrections
- 5% BSM effects at > 650 GeV in EW sector



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.

Conclusions

- Anthropic arguments alone can't solve Higgs-naturalness problem
  - To do requires making a very special (non-generic) landscape
    - Any reasonable landscape has a naturalness problem too.
    - Any landscape with no naturalness problem is itself highly artificial
      - **Find a fundamental theory that avoids this problem**!

- Resonances from QCD bound states
  - Useful for particles with stabilized lifetimes
  - Discovery for particles of high charge ($Q > 2/3$) OR complex messy decays

- Need more high-precision variables from theorists
  - Exercise: get high precision in diboson ratios
    - Ratios: small QCD corrections & uncertainties at high energy
  - Certainly good for SM studies, esp. EW effects
  - Need to study how/where sensitivity to BSM is improved

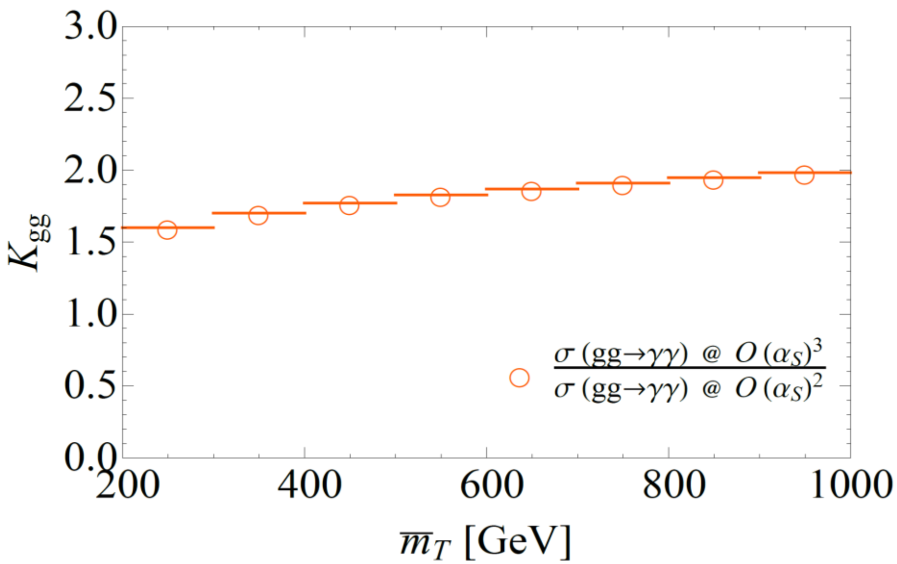
BACKUP SLIDES

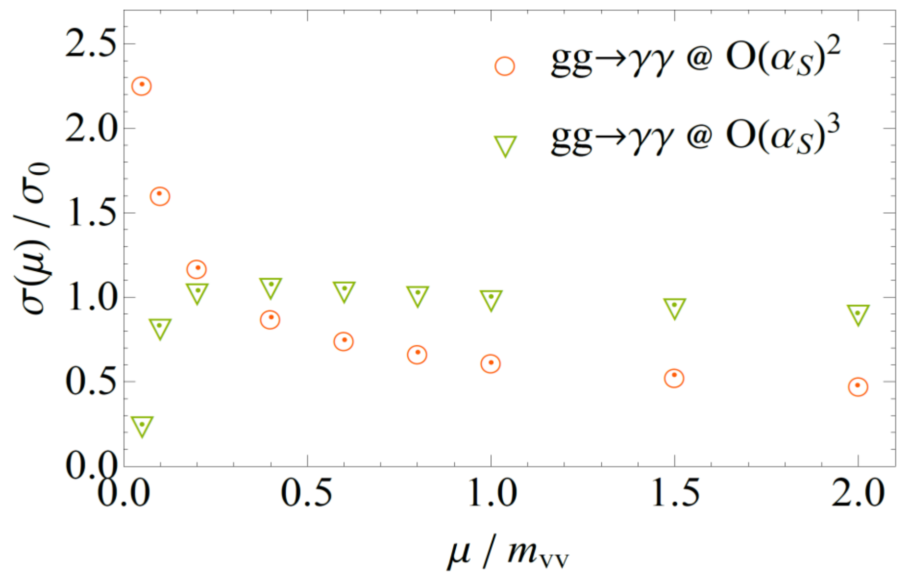
Selection Bias and Naturalness

- Selection bias (alone) does not solve the problem
    - Evolution of life ➔ old universe ➔ small cosmological constant
    - Evolution of life ➔ complex objects that aren't black holes
      ➔ small mass scales ➔… hierarchy
      … ??? ➔ **light SM Higgs boson** ????
  - Small mass scales can easily imply
    - Naturalness: SUSY, Technicolor
    - Weak-less universe Kribs Harnik Perez
    - Assortment of light fundamental nuclei-like particles … , Thaler
  - Does not logically require light SM Higgs boson
    - … unless dynamics forbids the other options!
      (i.e. "landscape" not enough.)

Scale setting

- For $gg \to \gamma\gamma$





- For the other processes

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

Processes with $W^{\pm}$

Custodial Limit

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q} \to V_1^0 V_2^0) = \frac{C_{12}^q}{\hat{s}^2}|a_1|^2\,, \qquad C_{ZZ}^q = \frac{1}{2}\,\frac{\pi\alpha_2^2 [redacted]}{N_c}\,(L^4 + [redacted])\ .$$

$$\underline{L \;=\; T_3}$$

[redacted]

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q}' \to W^{\pm}Z) = \frac{\pi|V_{ud}|^2\alpha_2^2}{N_c\,\hat{s}^2}\Big[[redacted]) + 4 [redacted] |a_3|^2 + \frac{1}{2}|a_\phi|^2\Big]$$

$$\frac{d\hat{\sigma}}{d\hat{t}}\,(q\bar{q} \to W^- W^+) \;=\; \frac{\pi\,\alpha_2^2}{N_c\,\hat{s}^2}\,\Big\{\frac{1}{16}\,|a_1|^2 \pm \frac{1}{2}(a_1 a_3) + 2\,|a_3|^2 + \Big[[redacted] T_3)^2\Big]\,|a_\phi|^2\Big\}$$

Upper signs for *q=u*
Lower signs for *q=d*

Processes with $W^{\pm}$

F-B Antisymmetries Are Equal

$$d\hat{\sigma}(W^{\pm}\gamma) + d\hat{\sigma}(W^{\pm}Z) = d\hat{\sigma}(w^{\pm}x) + d\hat{\sigma}(w^{\pm}w^{3}) + d\hat{\sigma}(\phi^{\pm}\phi^{3})$$

$\sim |a_1|^2$ $\sim |a_3|^2$ $\sim |a_\varphi|^2$

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q}' \to W^{\pm}\gamma) = \frac{\pi |V_{ud}|^2 \alpha_2^2 s_W^2}{N_c\, \hat{s}^2}\left[\frac{Y_L^2}{2}|a_1|^2 \pm 2Y_L(a_1 a_3) + 4|a_3|^2\right]$$

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q}' \to W^{\pm}Z) = \frac{\pi |V_{ud}|^2 \alpha_2^2}{N_c\, \hat{s}^2}\left[\frac{s_W^2 t_W^2 Y_L^2}{2}|a_1|^2 \mp 2s_W^2 Y_L(a_1 a_3) + 4c_W^2|a_3|^2 + \frac{1}{2}|a_\phi|^2\right]$$

Theoretically very robust! ☺
But experimentally useless
because WZ effect tiny! ☹

$$\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q} \to W^- W^+ \quad \ldots \quad 2\,|a_3|^2$$

$$+ \left[(t_W^2\, Y_R)^2 + (t_W^2\, Y_L + T_3)^2\right] |a_\phi|^2 \Bigg\}$$

Upper signs for *q=u*
Lower signs for *q=d*