Theoretical Perspective on SM and Higgs Physics at HL-LHC

Gavin P. Salam (with input from Michelangelo Mangano)
CERN

3rd ECFA High Luminosity LHC Experiments Workshop
4 October 2016, Aix-les-Bains, France

Why the Higgs sector is special

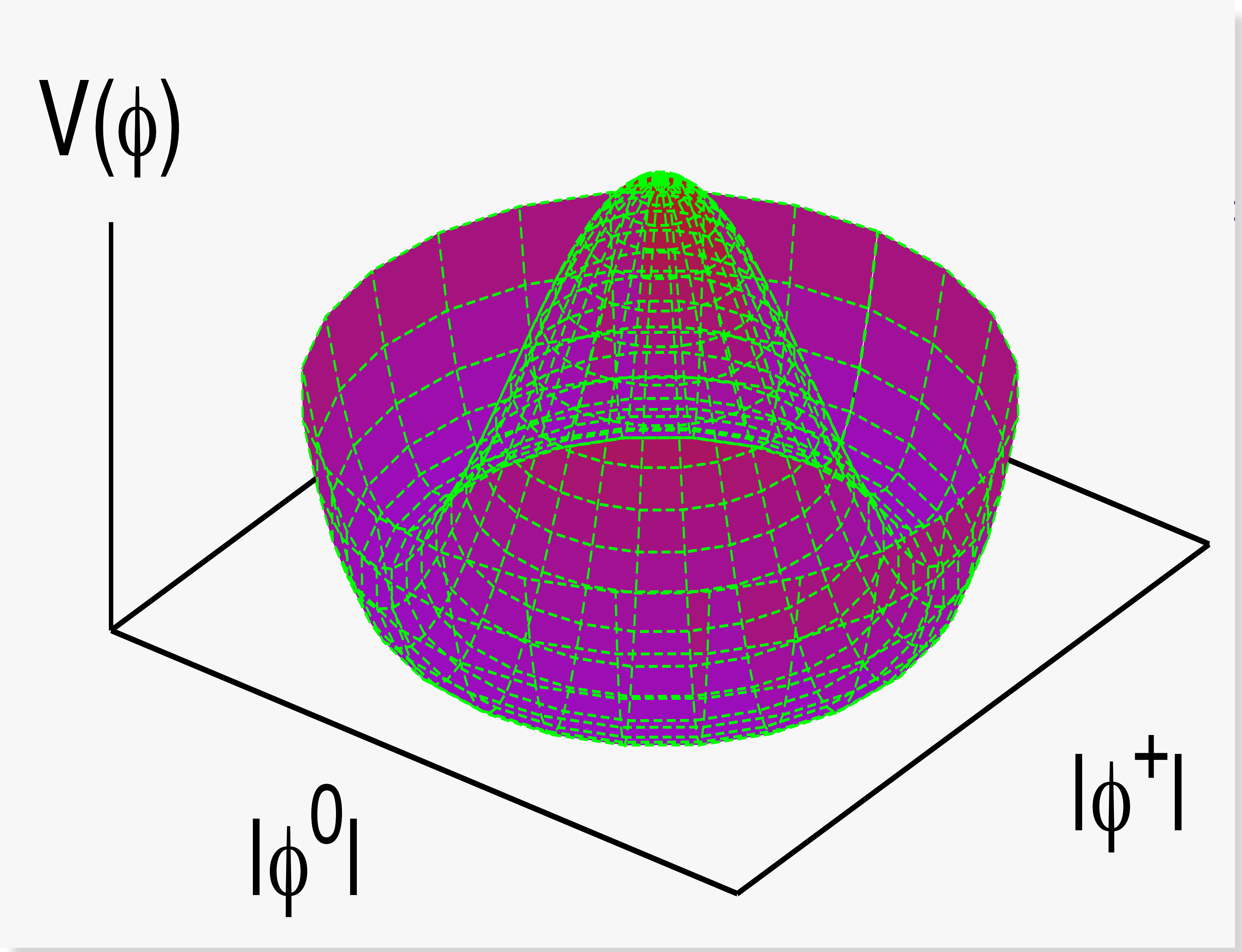
The theory is old (1960s-70s).

But the particle and its theory are unlike anything we've seen in nature.

- A fundamental scalar φ, i.e. spin 0
  (all other particles are spin 1 or 1/2)

- A potential $V(\varphi) \sim -\mu^2(\varphi\varphi^\dagger) + \lambda(\varphi\varphi^\dagger)^2$,
  which until now was limited to being theorists' "toy model" (φ^4)

- "Yukawa" interactions responsible for fermion masses, $y_i \phi \bar{\psi}\psi$, with couplings (y_i) spanning 5 orders of magnitude

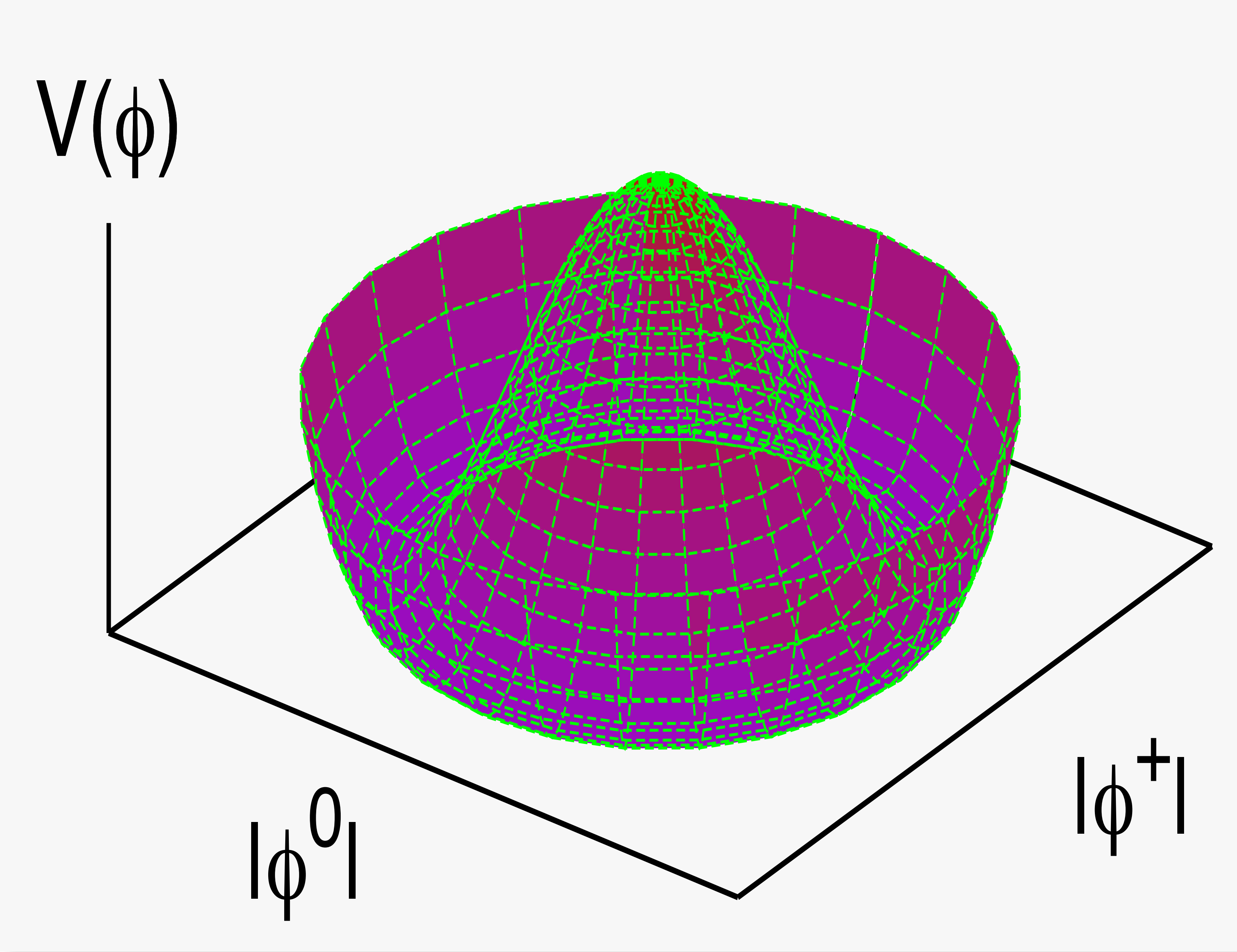


Why the Higgs sector is special

The theory is old (1960s-70s).

But the particle and its theory are unlike anything we've seen in nature.

- A fundamental scalar φ, i.e. spin 0 (all other particles are spin 1 or 1/2)
- A potential $V(\varphi) \sim -\mu^2(\varphi\varphi^\dagger) + \lambda(\varphi\varphi^\dagger)^2$, which until now was limited to being theorists' "toy model" (φ^4)
- "Yukawa" interactions responsible for fermion masses, $y_i \phi \bar{\psi} \psi$, with couplings (y_i) spanning 5 orders of magnitude



Higgs sector needs stress-testing

Is Higgs fundamental or composite?

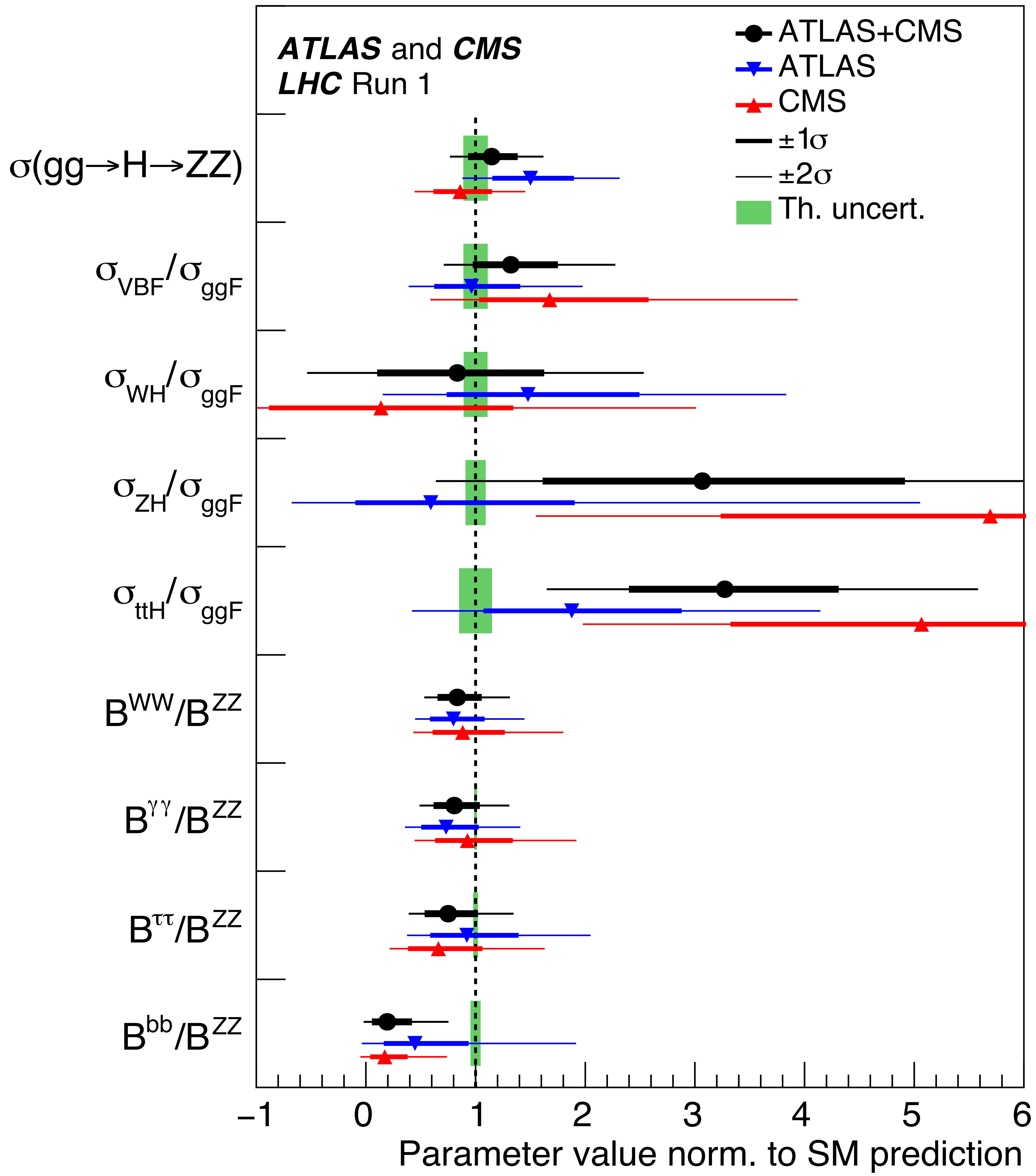
If fundamental, is it "minimal"?

Are Yukawa couplings responsible for masses of all generations?

Is potential really φ^4?

Is it a portal to new physics?

What do we know today? Broad picture looks standard-model like



Coupling to electroweak and 3rd generation looks standard

- we see expected rate of decays to ZZ and WW (and some evidence of VBF/VH)
- observation consistent with σ(gluon fusion) means top-coupling is probably standard
- fact that all cross sections look right also means b-coupling is probably standard (because it dominates in denominator of branching ratios)
- reasonable evidence that coupling to tau is standard (direct observation)

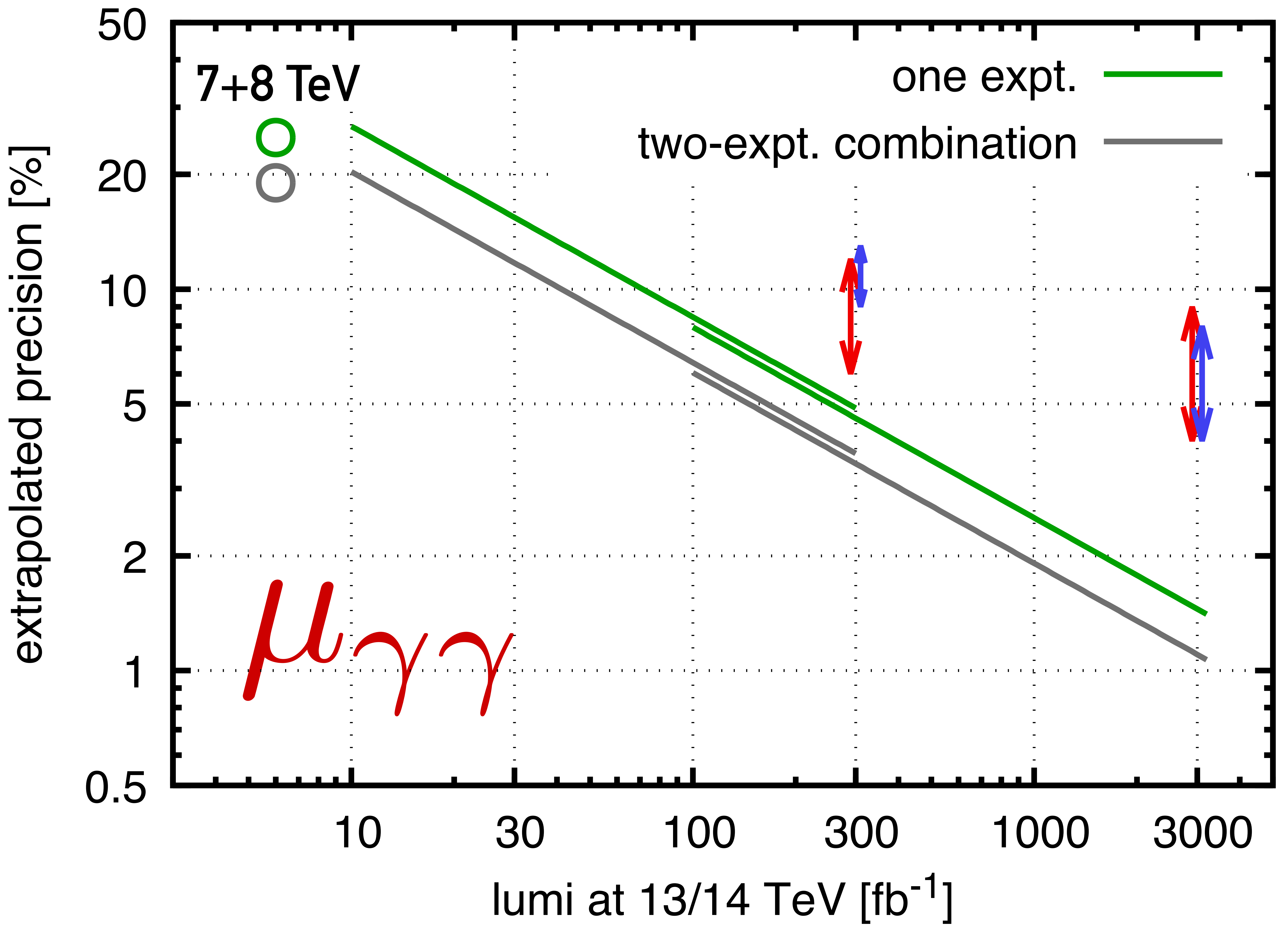
To see the data, as is, with very non-standard (t,b,τ,W,Z) couplings would require some degree of conspiracy.

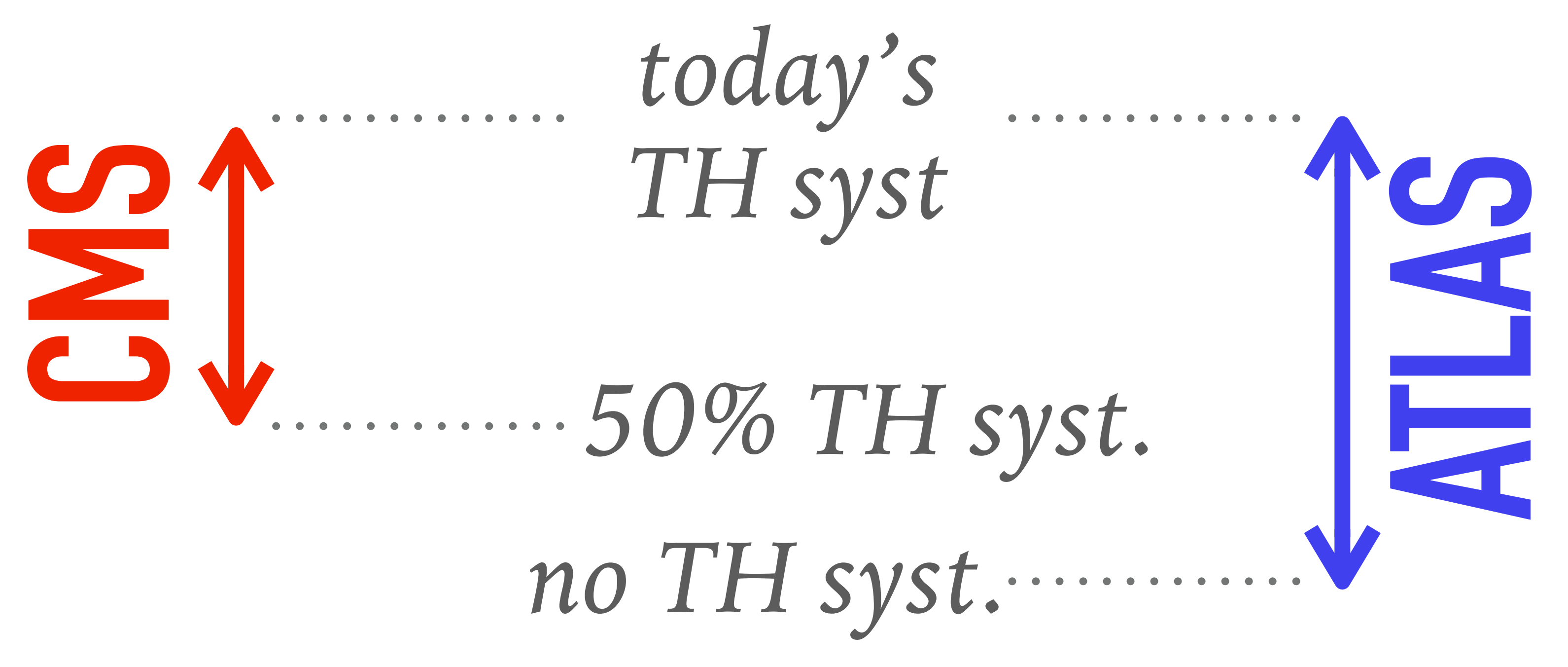
What does HL-LHC brings us?

- proof of expected coupling to 2nd generation ($H \to \mu\mu$)
- first exploration of Higgs potential (HH production)
- $\times 300$ sensitivity to rare decays involving new physics (cf. Matthew's talk yesterday)
- map out couplings to W/Z/3rd gen. with **precision** and across **broad kinematics,** which could reveal signs of
  - new particles in loops (too heavy to produce, or hard to observe)
  - non-fundamental nature of Higgs
  - or simply confirm, in detail, a highly non-trivial part of the standard model

precision Higgs

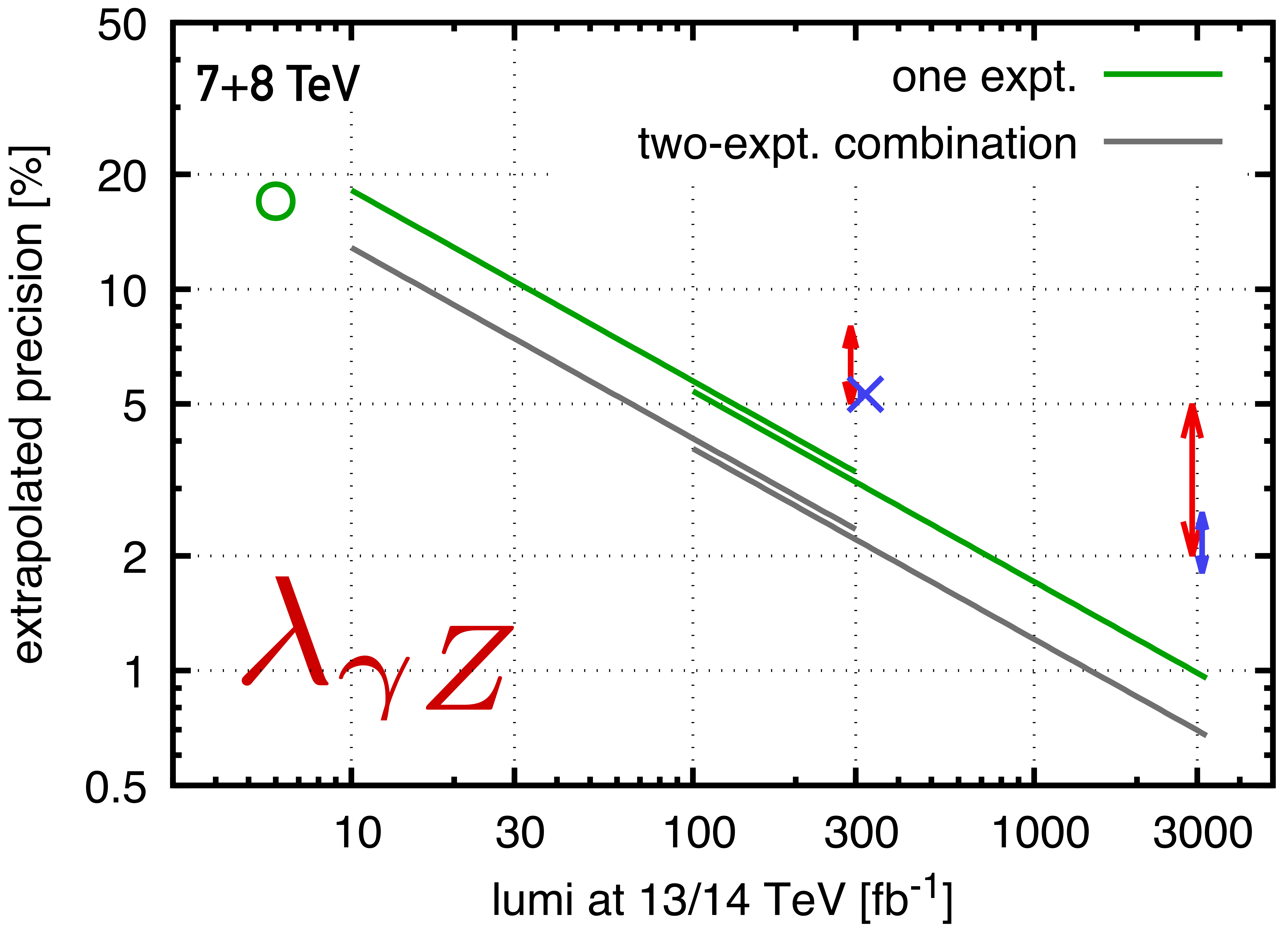
NAIVELY EXTRAPOLATE 7+8 TEV RESULTS (based on lumi and σ)

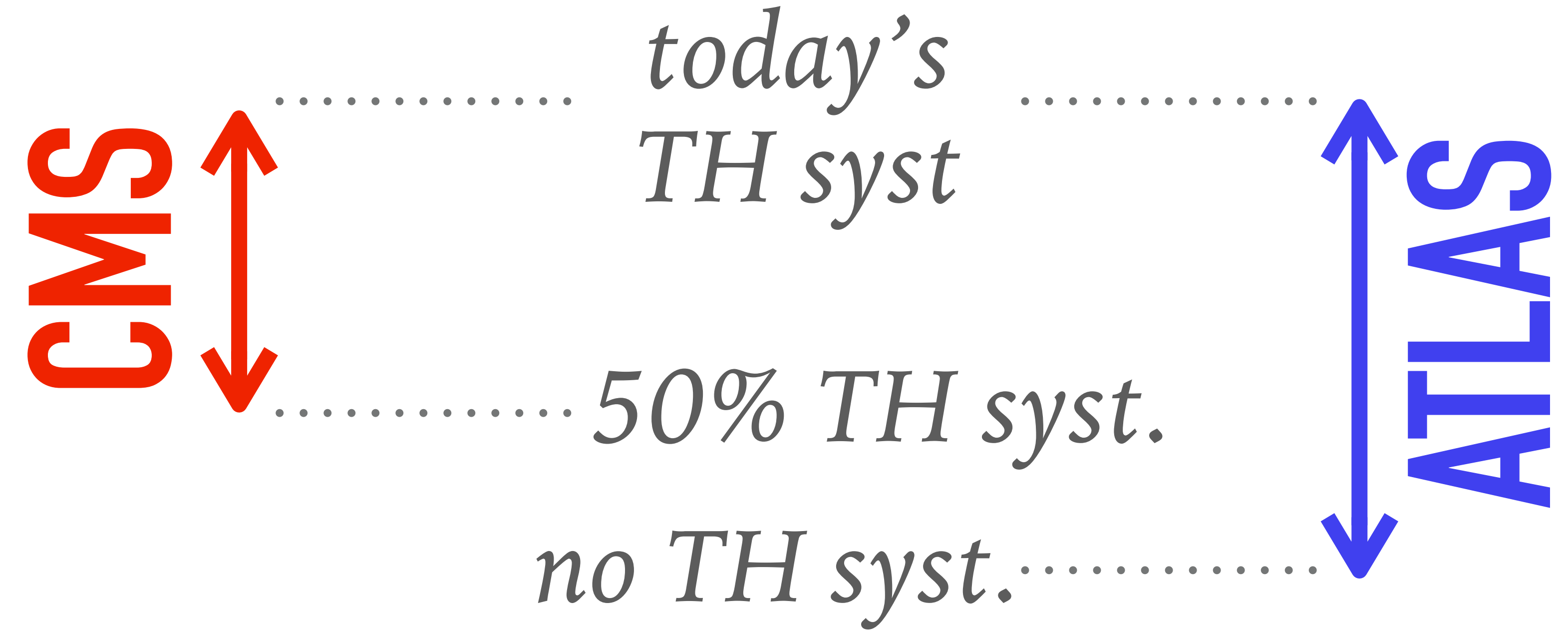




Extrapolation suggests that we get "precision" value from full lumi only if we aim for O(1%) or better precision

NAIVELY EXTRAPOLATE 7+8 TEV RESULTS (based on lumi and σ)





Extrapolation suggests that we get "precision" value from full lumi only if we aim for O(1%) or better precision

recent higgs theory progress

take gluon fusion as main example

consider theory calculations & inputs
as well as pathway for progress

GLUON-FUSION (13 TEV)

LHC HXSWG Yellow Report 3 (2013, NNLO)

m_H (GeV)	Cross Section (pb)	+QCD Scale %	-QCD Scale %	+(PDF+α_s) %	-(PDF+α_s) %
125.0	43.92	+7.4	-7.9	+7.1	-6.0

$$48.58\,\text{pb} \pm 1.89\,\text{pb}(3.9\%)\ (\text{theory}) \pm 1.56\,\text{pb}(3.20\%)\ (\text{PDF}+\alpha_s)$$

Anastasiou et al., (1602.00695, N3LO) + HXSWG YR4

GLUON-FUSION (13 TEV)

LHC HXSWG Yellow Report 3 (2013, NNLO)

m_H (GeV)	Cross Section (pb)	+QCD Scale %	-QCD Scale %	+(PDF+α_s) %	-(PDF+α_s) %
125.0	43.92	+7.4	-7.9	+7.1	-6.0

+11% from scale choice, PDFs, N3LO, …

$$48.58\,\mathrm{pb} \pm 1.89\,\mathrm{pb}(3.9\%)\ (\mathrm{theory}) \pm 1.56\,\mathrm{pb}(3.20\%)\ (\mathrm{PDF}+\alpha_s)$$

Anastasiou et al., (1602.00695, N3LO) + HXSWG YR4

GLUON-FUSION (13 TEV)

LHC HXSWG Yellow Report 3 (2013, NNLO)

m_H (GeV)	Cross Section (pb)	+QCD Scale %	-QCD Scale %	+(PDF+α_s) %	-(PDF+α_s) %
125.0	43.92	+7.4	-7.9	+7.1	-6.0

CMS scenario 2 (reduction by 50%) already achieved!

$$48.58\,\mathrm{pb} \pm 1.89\,\mathrm{pb}(3.9\%)\ (\mathrm{theory}) \pm 1.56\,\mathrm{pb}(3.20\%)\ (\mathrm{PDF}+\alpha_s)$$

Anastasiou et al., (1602.00695, N3LO) + HXSWG YR4

GLUON-FUSION (13 TEV)

LHC HXSWG Yellow Report 3 (2013, NNLO)

m_H (GeV)	Cross Section (pb)	+QCD Scale %	-QCD Scale %	+(PDF+α_s) %	-(PDF+α_s) %
125.0	43.92	+7.4	-7.9	+7.1	-6.0

nearly 50%
reduction
here too

$$48.58\,\text{pb} \pm 1.89\,\text{pb}(3.9\%)\ (\text{theory}) \pm 1.56\,\text{pb}(3.20\%)\ (\text{PDF}+\alpha_s)$$

Anastasiou et al., (1602.00695, N3LO) + HXSWG YR4

GLUON-FUSION (13 TEV)

LHC HXSWG Yellow Report 3 (2013, I

m_H (GeV)	Cross Section (pb)	+QCD Scale %	-QCD Scal
125.0	43.92	+7.4	-7.9

nearly 50% reduction here too

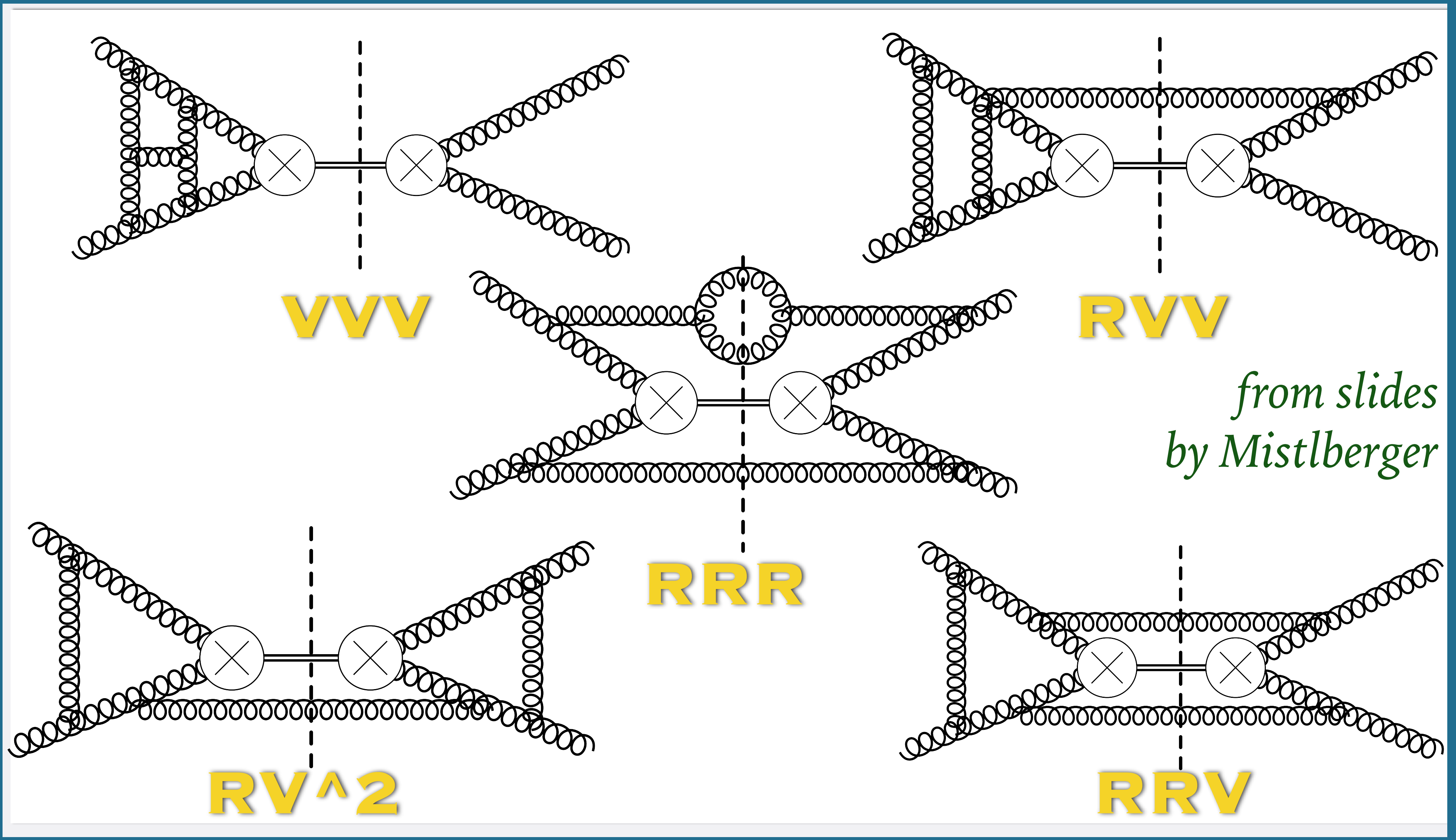
$$48.58\,\text{pb} \pm 1.89\,\text{pb}(3.9\%)\ (\text{theory}) \pm 1.56\,\text{pb}(3.20\%)\ (\text{PDF}+\alpha_s)$$

Anastasiou et al., (1602.00695, N3LO) + HXSWG YR4

N3LO Higgs production

Anastasiou, Duhr, Dulat, Herzog, Mistlberger ’15-16

100,000 diagrams



GLUON-FUSION (13 TEV) — theory uncertainty

Anastasiou et al., (1602.00695, N3LO)

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t, b, c)$	$\delta(1/m_t)$
$+0.10$ pb -1.15 pb	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$+0.21\%$ -2.37%	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

GLUON-FUSION (13 TEV) — theory uncertainty

Anastasiou et al., (1602.00695, N3LO)

$\delta(\text{scale})$	$\delta(\text{trunc})$	$\delta(\text{PDF-TH})$	$\delta(\text{EW})$	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

added linearly $^{+4.6\%}_{-6.7\%}$

added in quadrature $^{+2.1\%}_{-3.1\%}$

HXSWG Gaussian ±3.9%

vs. ±7.5% in YR4

GLUON-FUSION (13 TEV) — theory uncertainty

Anastasiou et al., (1602.00695, N3LO)

$\delta(\text{scale})$	$\delta(\text{trunc})$	$\delta(\text{PDF-TH})$	$\delta(\text{EW})$	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

improvement needs N4LO (or new insight) i.e. unlikely to get better in next decade

progress requires N3LO PDF fits (may be possible in next years?)

likely to improve with new calculations in next years?

added linearly $^{+4.6\%}_{-6.7\%}$

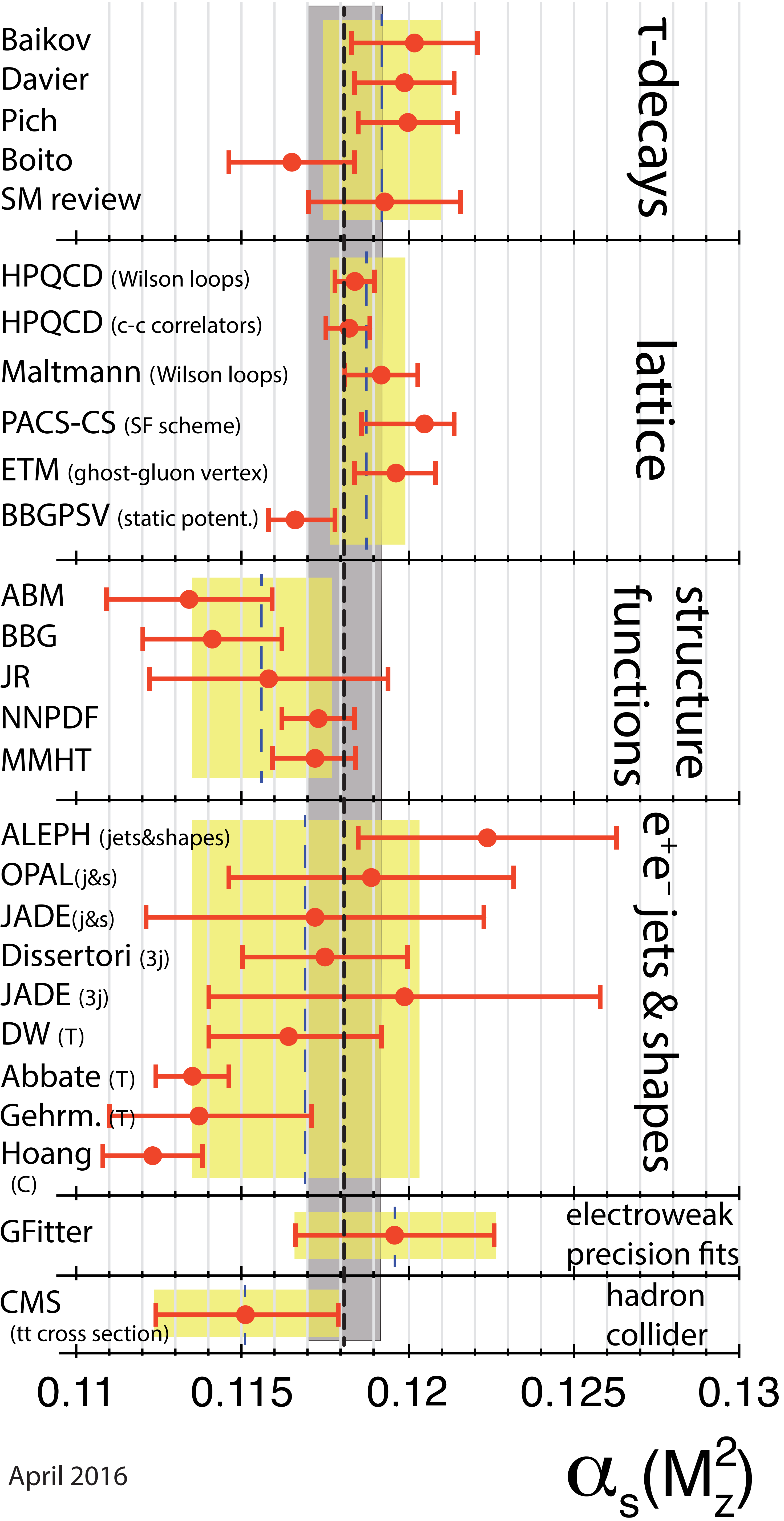
added in quadrature $^{+2.1\%}_{-3.1\%}$

HXSWG Gaussian ±3.9%

vs. ±7.5% in YR4

the inputs

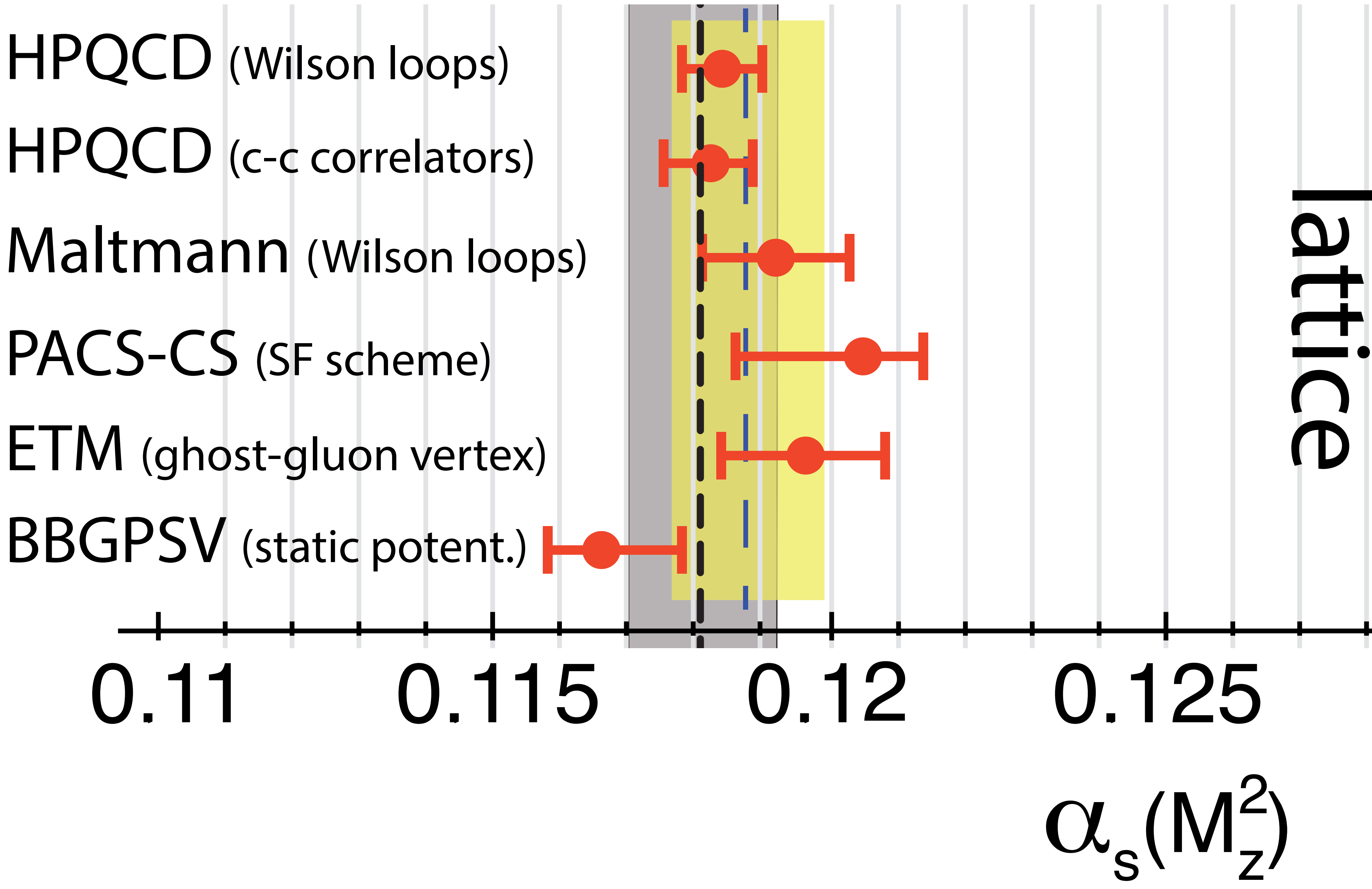
strong coupling (e.g. $\pm 2.6\%$ on ggF)
PDFs (e.g. $\pm 1.9\%$ on ggF)



PDG World Average: $\alpha_s(M_Z) = 0.1181 \pm 0.0011$ (0.9%). WHAT WAY FORWARD?

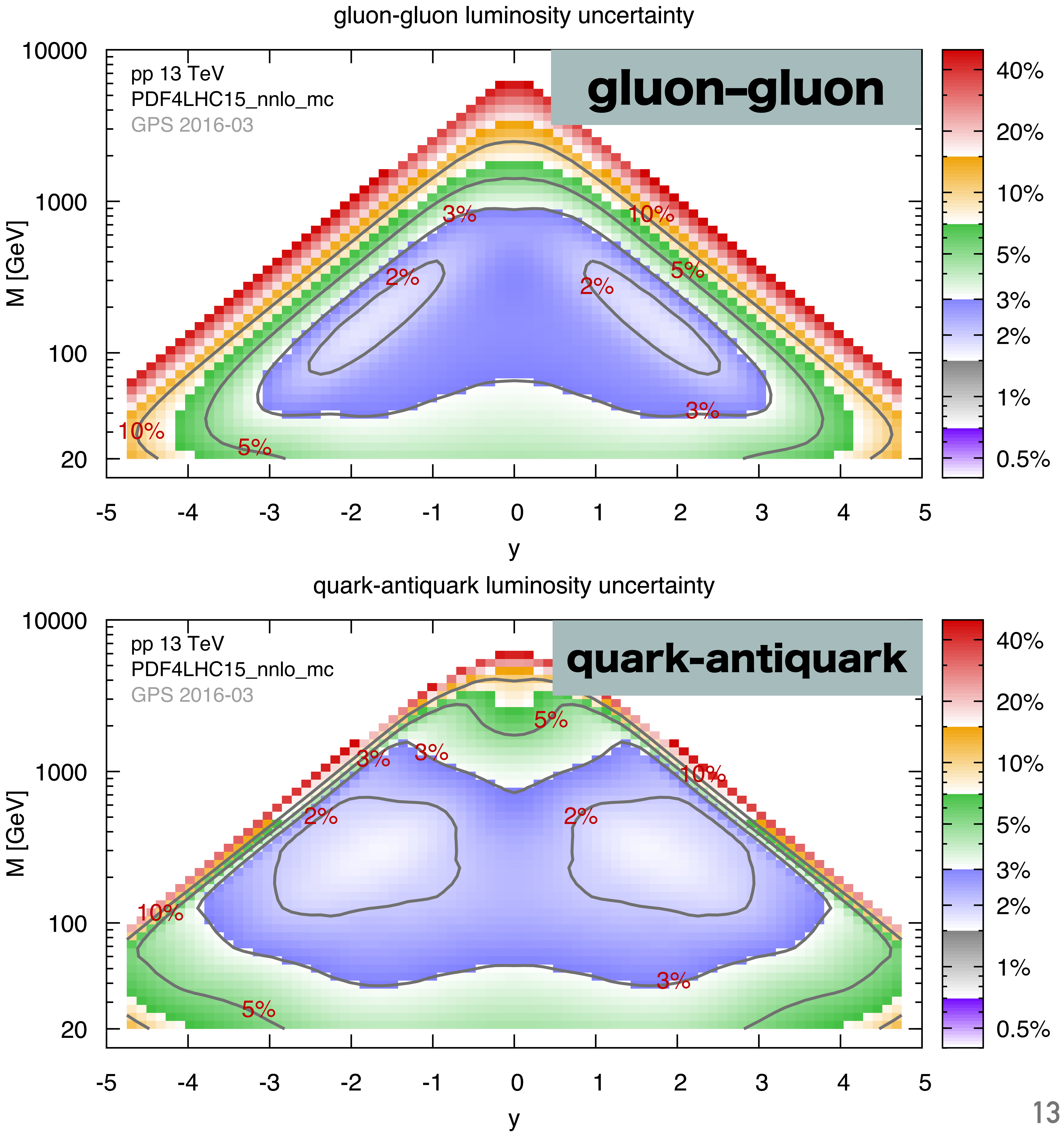
- For gluon-fusion & ttH, this comes in squared. It also correlates with the PDFs and affects backgrounds.

- To go beyond 1%, best hope is probably lattice QCD — on a 10-year timescale, there will likely be enough progress that multiple groups will have high-precision determinations



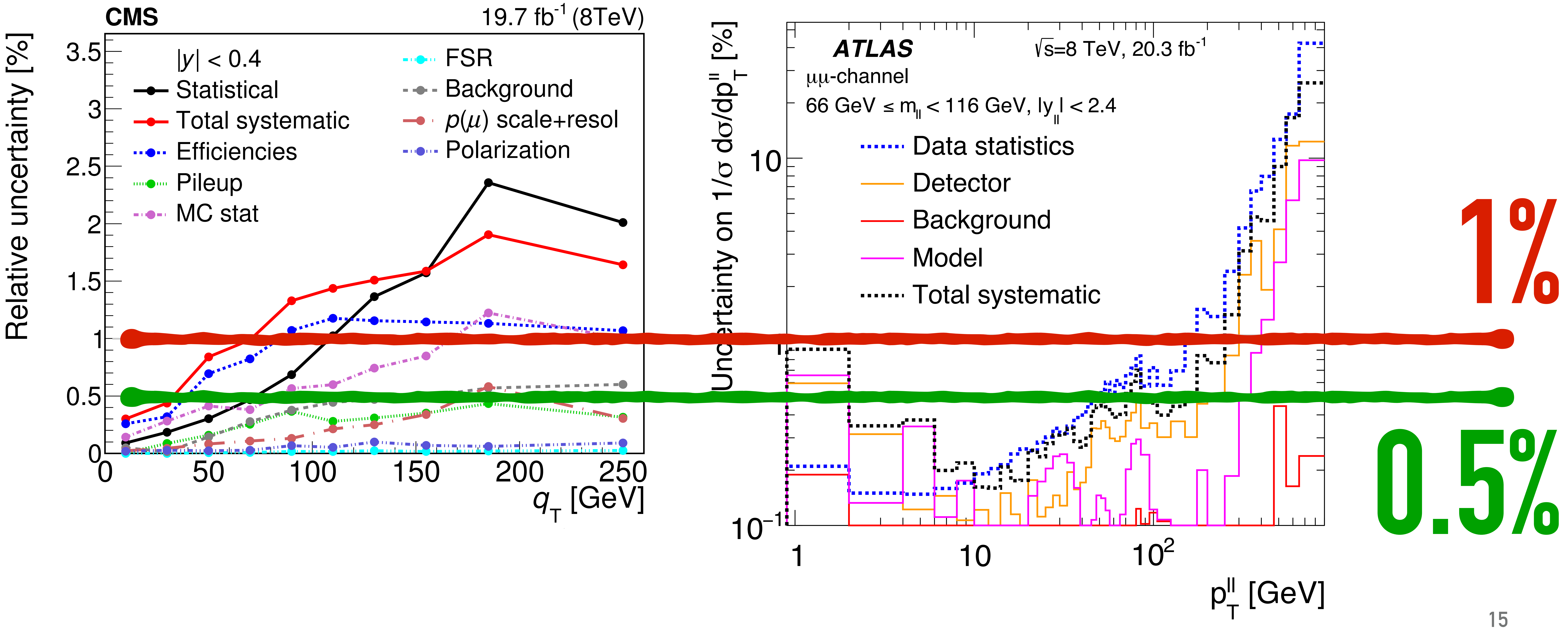
PDFs: WHAT ROUTE FOR PROGRESS?

- Current status is 2–3% for core "precision" region
- Path to ~1% is not clear — e.g. Z p_T's strongest constraint is on qg lumi, which is already best known (why?)
- It'll be interesting to revisit the question once ttbar, incl. jets, Z p_T, etc. have all been incorporated at NNLO
- **Can we get measurements and theory to 1% accuracy?**



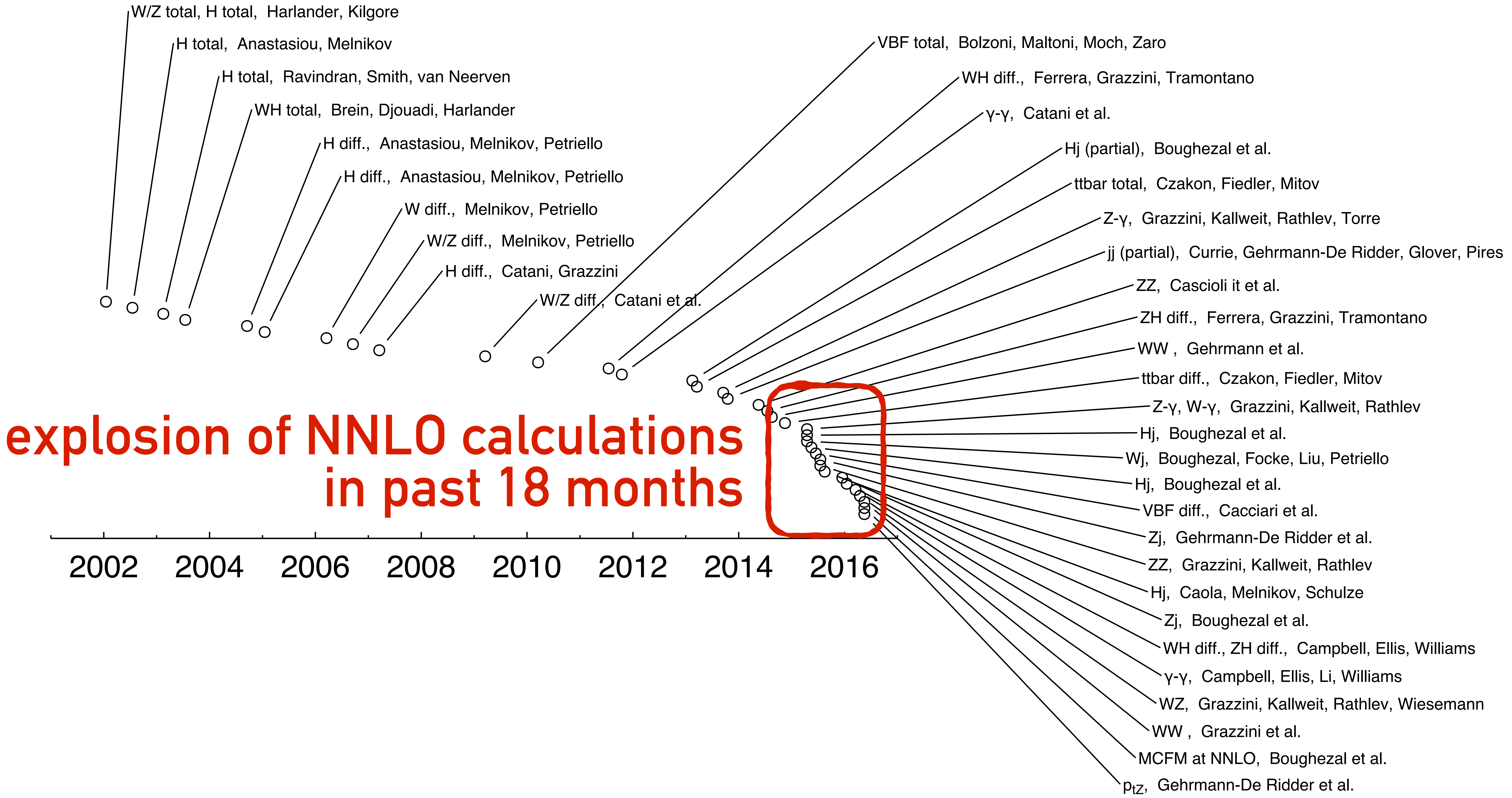
is 1% possible at a hadron collider?

Z p_T distribution: 0.5–1% precision!

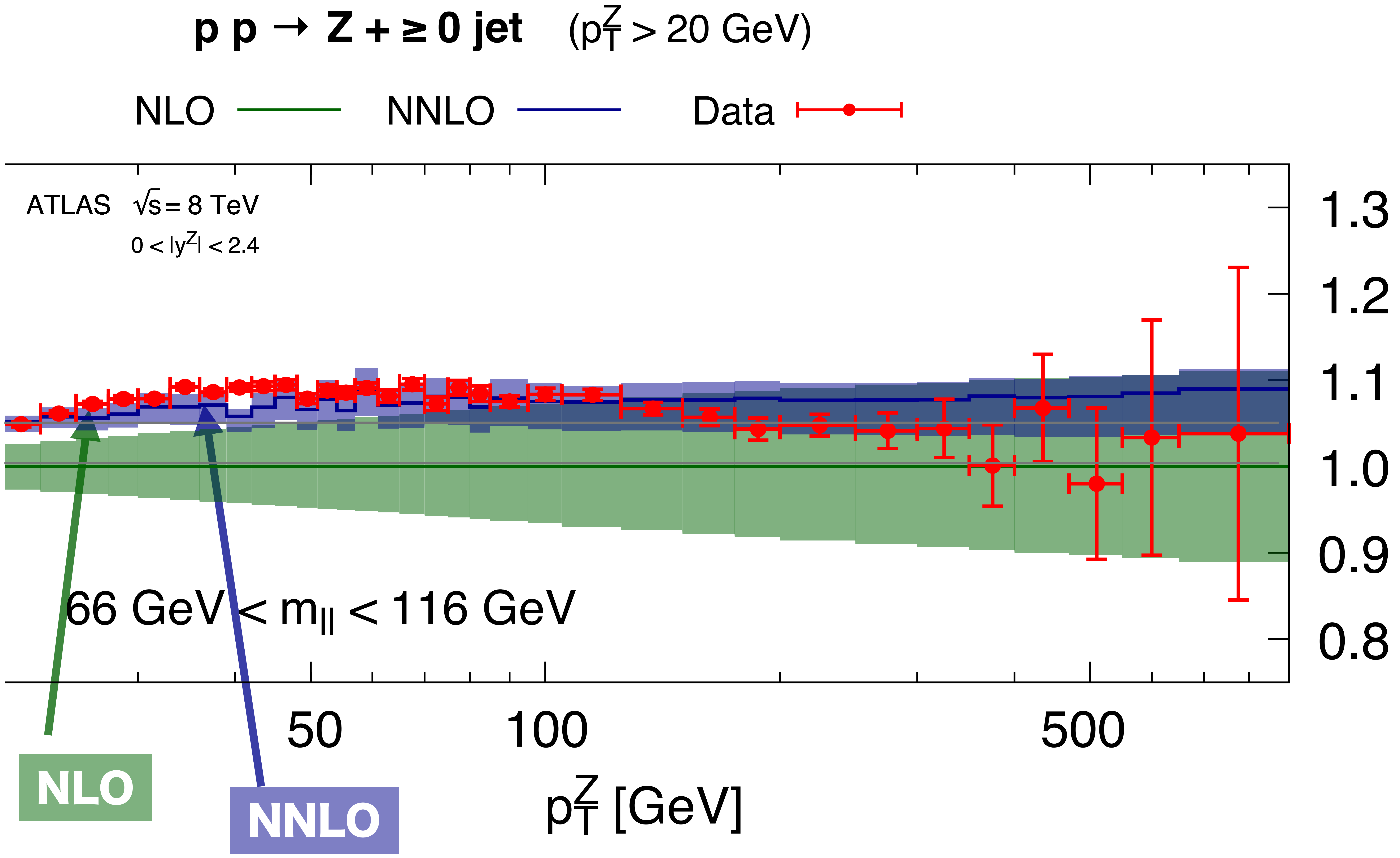


NNLO hadron-collider calculations v. time

as of mid June



Z p_T: Data v. two theory calculations

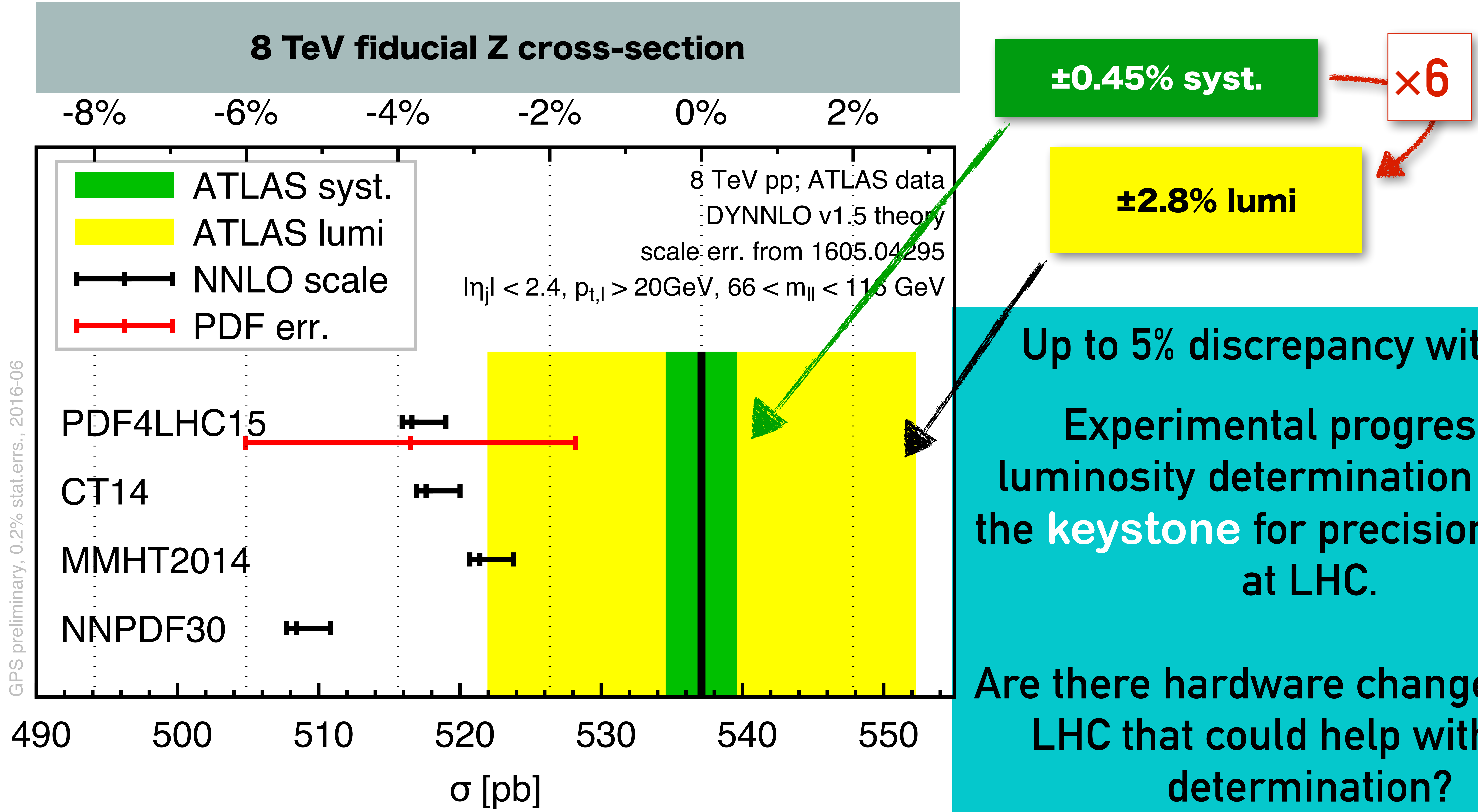


Gehrmann-de Ridder, Gehrmann Glover, Huss & Morgan

arXiv:1605.04295

NNLO ~ ±1.5 %

There are, however, issues. Notably in Z production



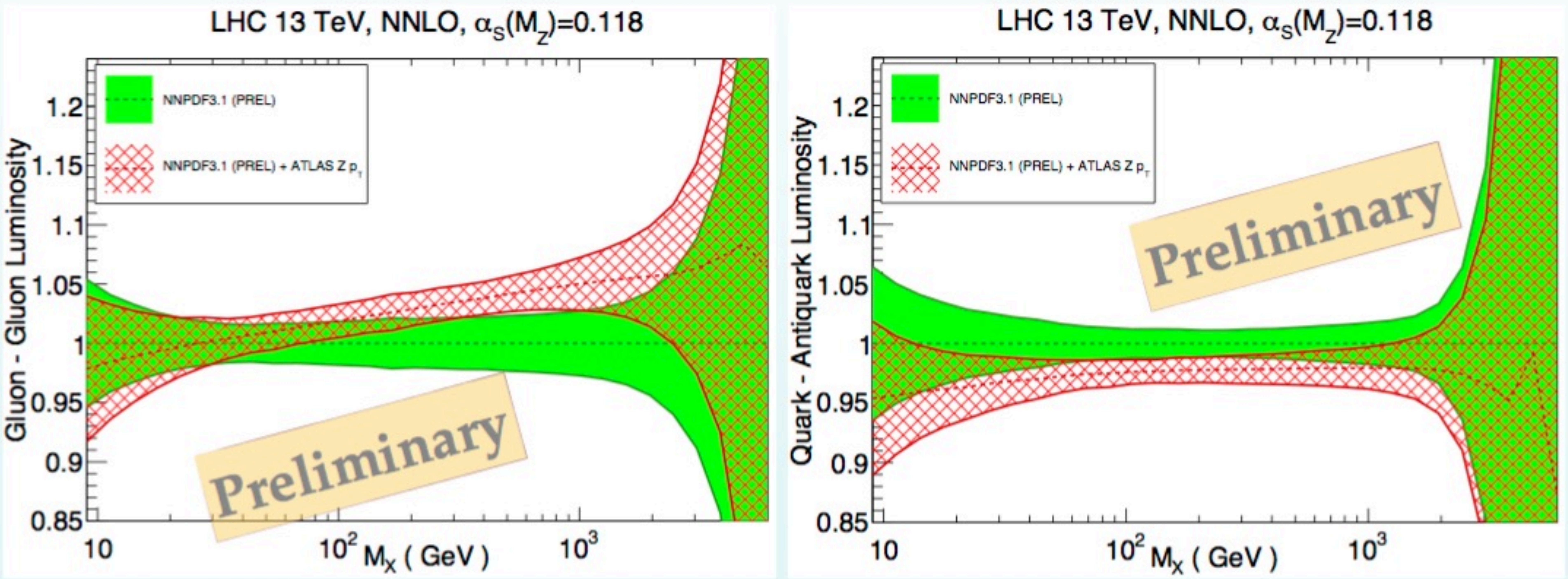
Up to 5% discrepancy with data

Experimental progress on luminosity determination may be the **keystone** for precision physics at LHC.

Are there hardware changes to HL-LHC that could help with lumi determination?

Impact of Z p_T spectrum on PDF fits

Preliminary NNPDF3.1 NNLO fits suggest a **sizeable impact** of the **LHC Z p_T data** on the PDFs



Including the LHC Z p_T data could be a **game-changer** in global NNLO PDF fits ......

data-driven workarounds?

theory may have a hard limit
e.g. non-perturbative effects for cuts on jets

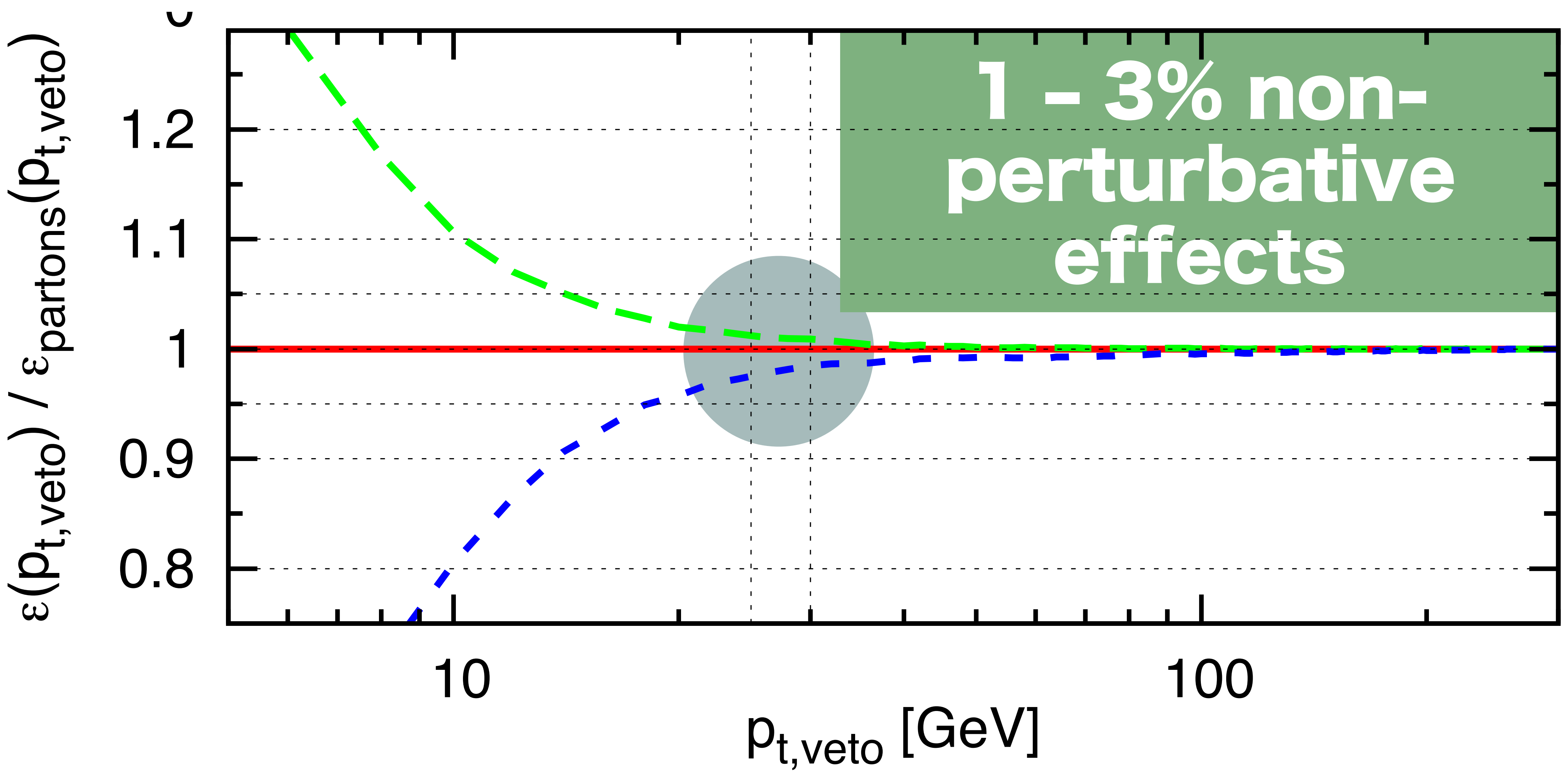
& are there issues in data-driven workarounds?

E.g. jet veto efficiency for H → WW*

LHC 13 TeV	$\epsilon^{\mathrm{N^3LO+NNLL+LL_R}}$
$p_{t,\mathrm{veto}} = 25\,\mathrm{GeV}$	$0.539^{+0.017}_{-0.008}$
$p_{t,\mathrm{veto}} = 30\,\mathrm{GeV}$	$0.608^{+0.016}_{-0.007}$

perturbative uncert: 1.5-3%

Anastasiou, Duhr, Dulat, Herzog & Mistlberger 1503.06056
Boughezal, Caola, Melnikov, Petriello & Schulze 1504.07922
Banfi, Caola, Dreyer, Monni, GPS, Zanderighi & Dulat 1511.02886



Banfi, GPS, Zanderighi 1203.5773

Measurements of H→ZZ* and γγ can constrain this directly.

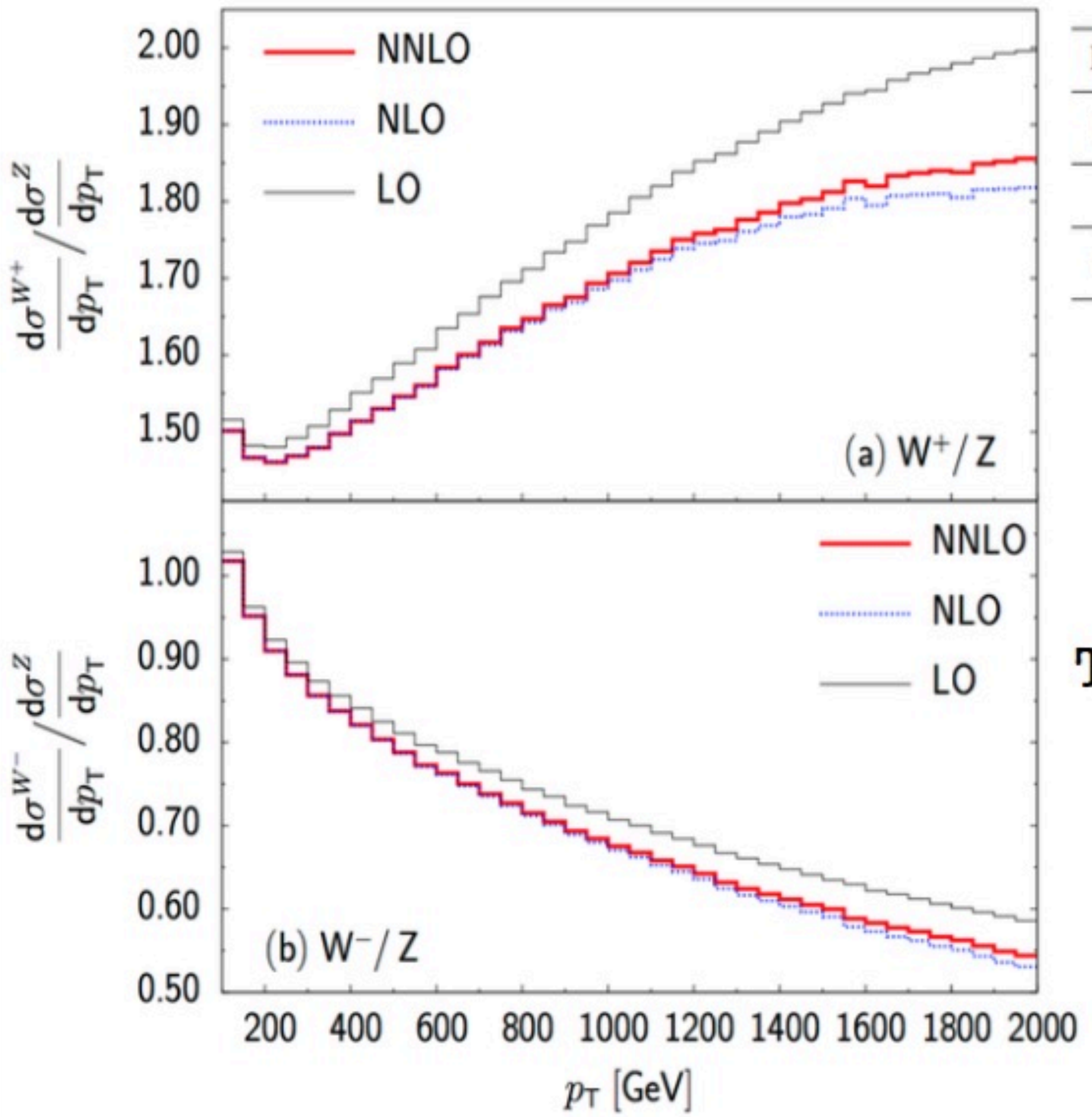
Run I: ~ 40 evts. equiv.

HL-LHC: ~ 15k events equiv.

→ 1% uncertainties?

advocated notably by MLM

EW radiation correction differences in W+jets and Z+jets.



Electroweak corrections to hadronic production of W bosons at large transverse momenta
Johann H. Kühn, A. Kulesza, S. Pozzorini, M. Schulze.
Nucl.Phys.B797:27-77,2008

EW correction by theoretical calculations						
E1 (250-300)	E2 (300-350)	E3 (350-400)	E4 (400-500)	E5 (500-600)	E6 (600-700)	E7 (>700)
$\left(-0.4^{+1.6}_{-0.8}\right)\%$	$\left(0.1^{+1.6}_{-1.0}\right)\%$	$\left(-0.7^{+1.8}_{-1.2}\right)\%$	$\left(0.2^{+1.8}_{-1.4}\right)\%$	$\left(0.4^{+2.1}_{-1.9}\right)\%$	$\left(1.5^{+2.5}_{-2.3}\right)\%$	$\left(1.7^{+2.4}_{-3.5}\right)\%$
I1 (>250)	I2 (>300)	I3 (>350)	I4 (>400)	I5 (>500)	I6 (>600)	I7 (>700)
$\left(-0.3^{+1.6}_{-1.0}\right)\%$	$\left(-0.1^{+1.7}_{-1.3}\right)\%$	$\left(-0.1^{+2.2}_{-1.5}\right)\%$	$\left(0.4^{+2.1}_{-1.7}\right)\%$	$\left(0.8^{+2.4}_{-2.2}\right)\%$	$\left(1.6^{+2.3}_{-2.8}\right)\%$	$\left(1.7^{+2.4}_{-3.5}\right)\%$

W/Z QCD/EWK corrections at higher orders computed by authors of the paper for our different event selections.

They use NNPDF. The uncertainties in the calculation are dominated by the *photon induced PDFs* .

Since the uncertainties are as large as the corrections themselves, the prescription followed by us was not to apply the corrections, but rather take the central total deviation (of W/Z+jet ratio), adding linearly the biggest error bar, as uncertainty for the Z(νν) background.

Ability to transfer input from W control regions to Z backgrounds relies on theoretical control on EW corrections. These modify in different ways W and Z spectra, and grow with p_T. Large statistics needed to monitor behaviour of EW effects at the largest p_T

high-p_T Higgs

equally interesting:
off-shell Higgs

Higgs as a BSM probe: precision vs dynamic reach

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots$$

$$O = | \langle f|L|i\rangle |^2 = O_{SM} \left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

Higgs as a BSM probe: precision vs dynamic reach

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots$$

$$O = |\langle f|L|i\rangle|^2 = O_{SM}\left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

For H decays, or inclusive production, $\mu \sim O(v, m_H)$

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

⇒ **precision** probes large Λ

e.g. $\delta O = 1\% \Rightarrow \Lambda \sim 2.5$ TeV

Higgs as a BSM probe: precision vs dynamic reach

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots$$

$$O = | \langle f|L|i\rangle |^2 = O_{SM} \left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

For H decays, or inclusive production, $\mu \sim O(v, m_H)$

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

⇒ **precision** probes large Λ

e.g. $\delta O = 1\% \Rightarrow \Lambda \sim 2.5$ TeV

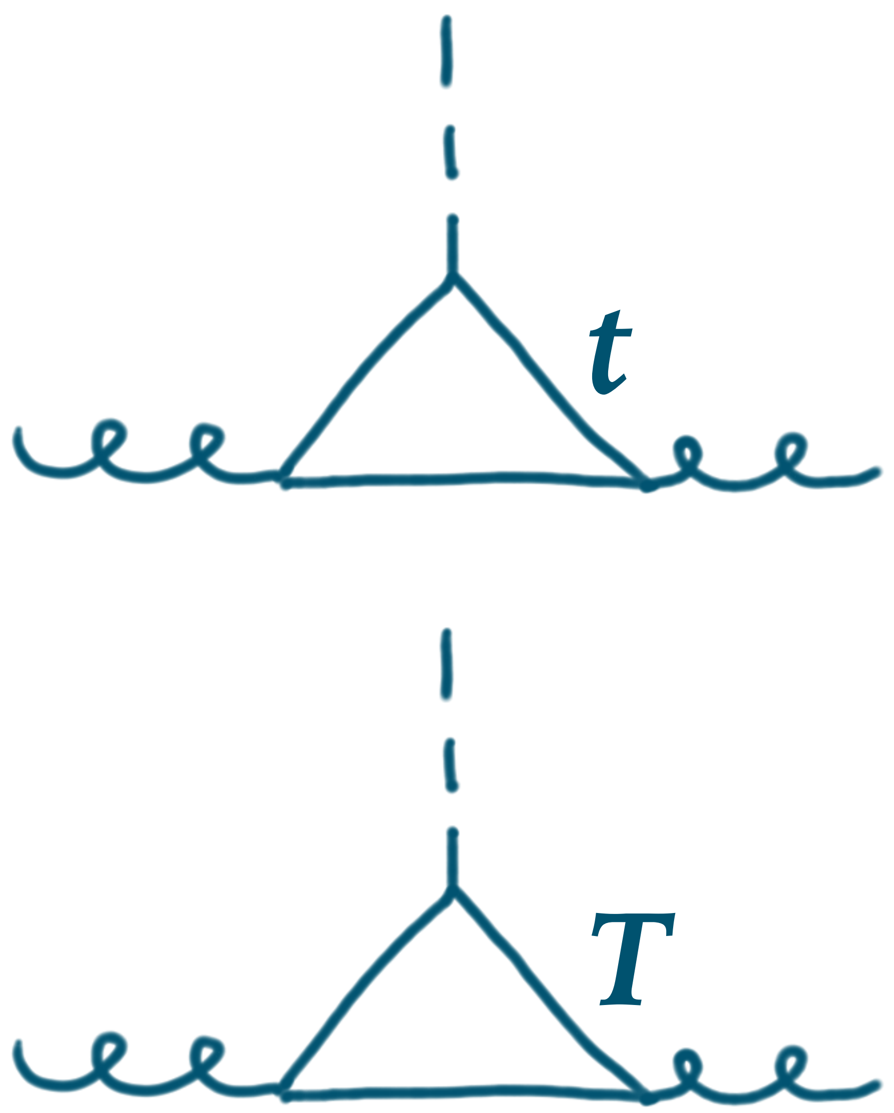
For H production off-shell or with large momentum transfer Q, $\mu \sim O(Q)$

$$\delta O_Q \sim \left(\frac{Q}{\Lambda}\right)^2$$

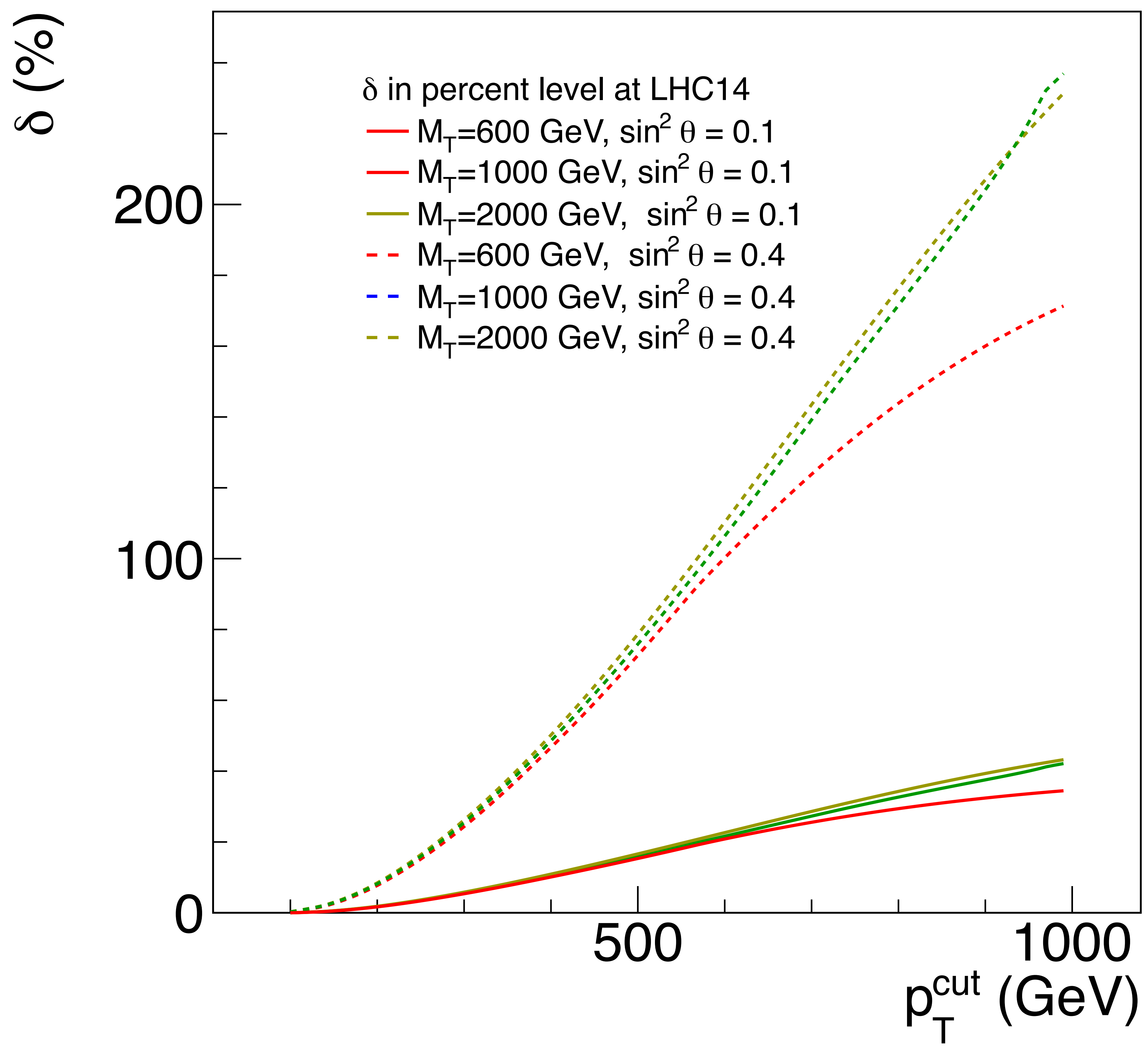
⇒ **kinematic reach** probes large Λ even if precision is low

e.g. $\delta O_Q = 15\%$ at Q=1 TeV ⇒ $\Lambda \sim 2.5$ TeV

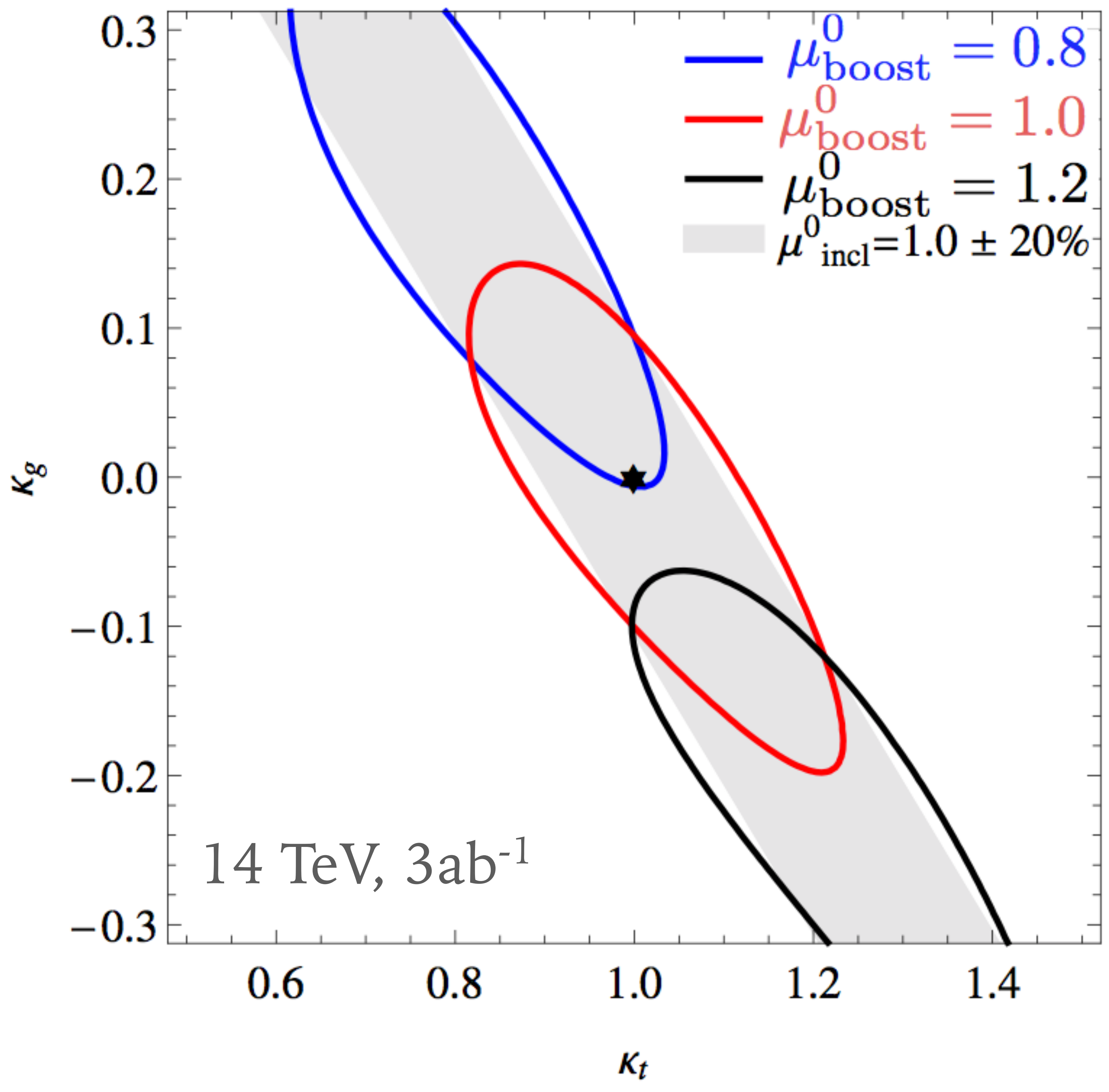
High-pt Higgs (e.g. to distinguish κ_g and κ_t)



Structure of loops is best probed by going to high p_T



A.Banfi, A.Martin, V.Sanz (2013)



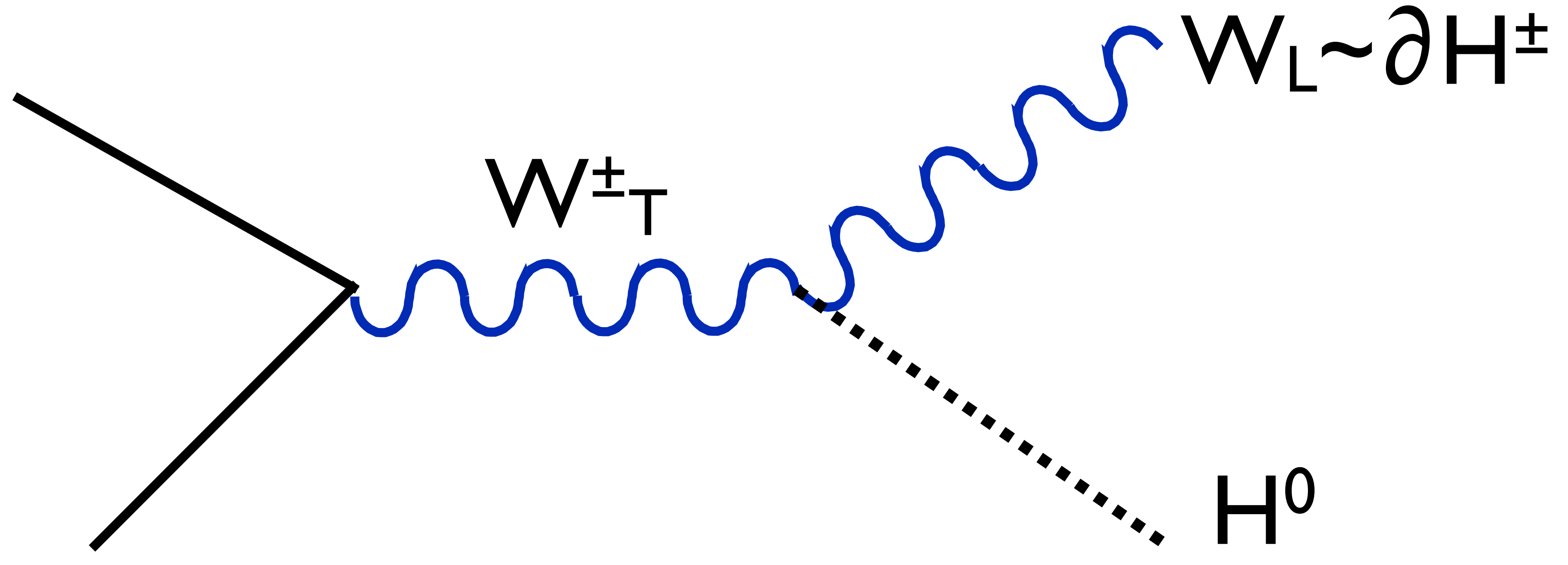
C.Grojean et al. (2013)

see also Azatov, Paul (2013)
S.Dawson,I.Lewis,M.Zeng (2014)

what are experimental prospects?
are there any theory-issues to be solved?

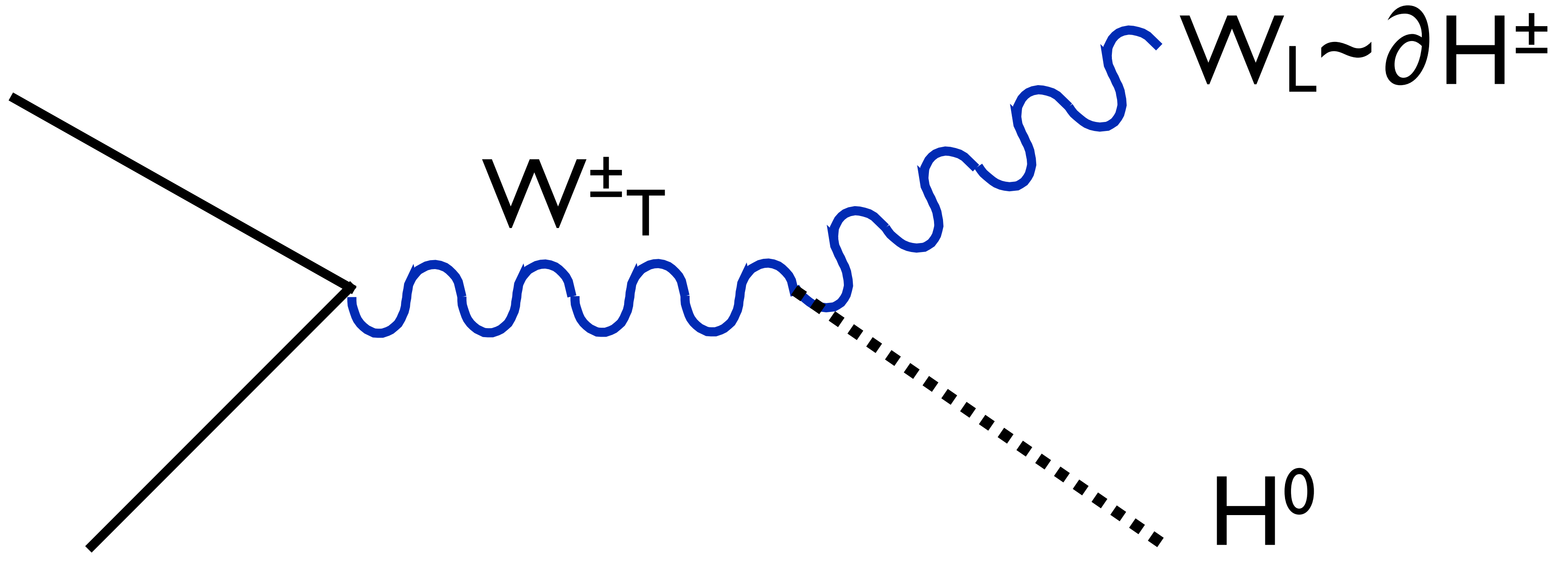
VH prodution at large m(VH)

See e.g.
Biekötter, Knochel, Krämer, Liu, Riva,
arXiv:1406.7320



VH prodution at large m(VH)

See e.g.
Biekötter, Knochel, Krämer, Liu, Riva, arXiv:1406.7320



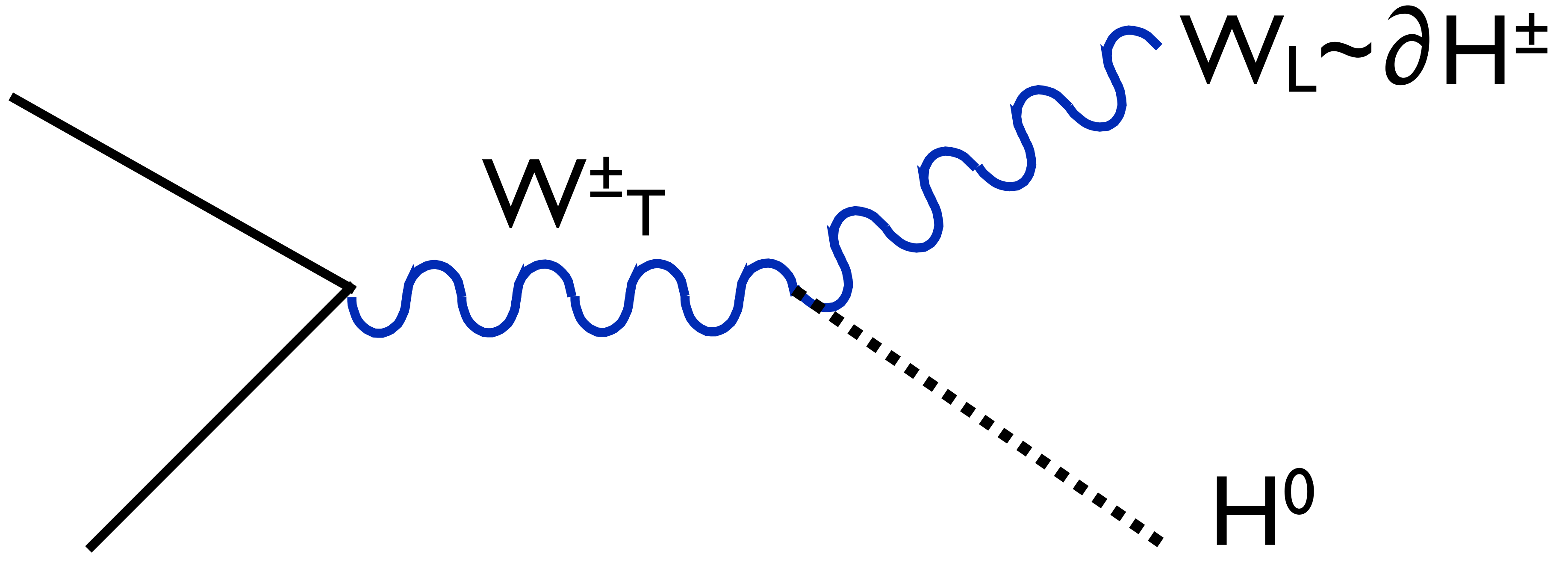
In presence of a higher-dim op such as:

$$L_{D=6} = \frac{ig}{2} \frac{c_W}{\Lambda^2} \left(H^\dagger \sigma^a D^\mu H\right) D^\nu V^a_{\mu\nu}$$

$$\frac{\sigma}{\sigma_{SM}} \sim \left(1 + c_W \frac{\hat{s}}{\Lambda^2}\right)^2$$

VH prodution at large m(VH)

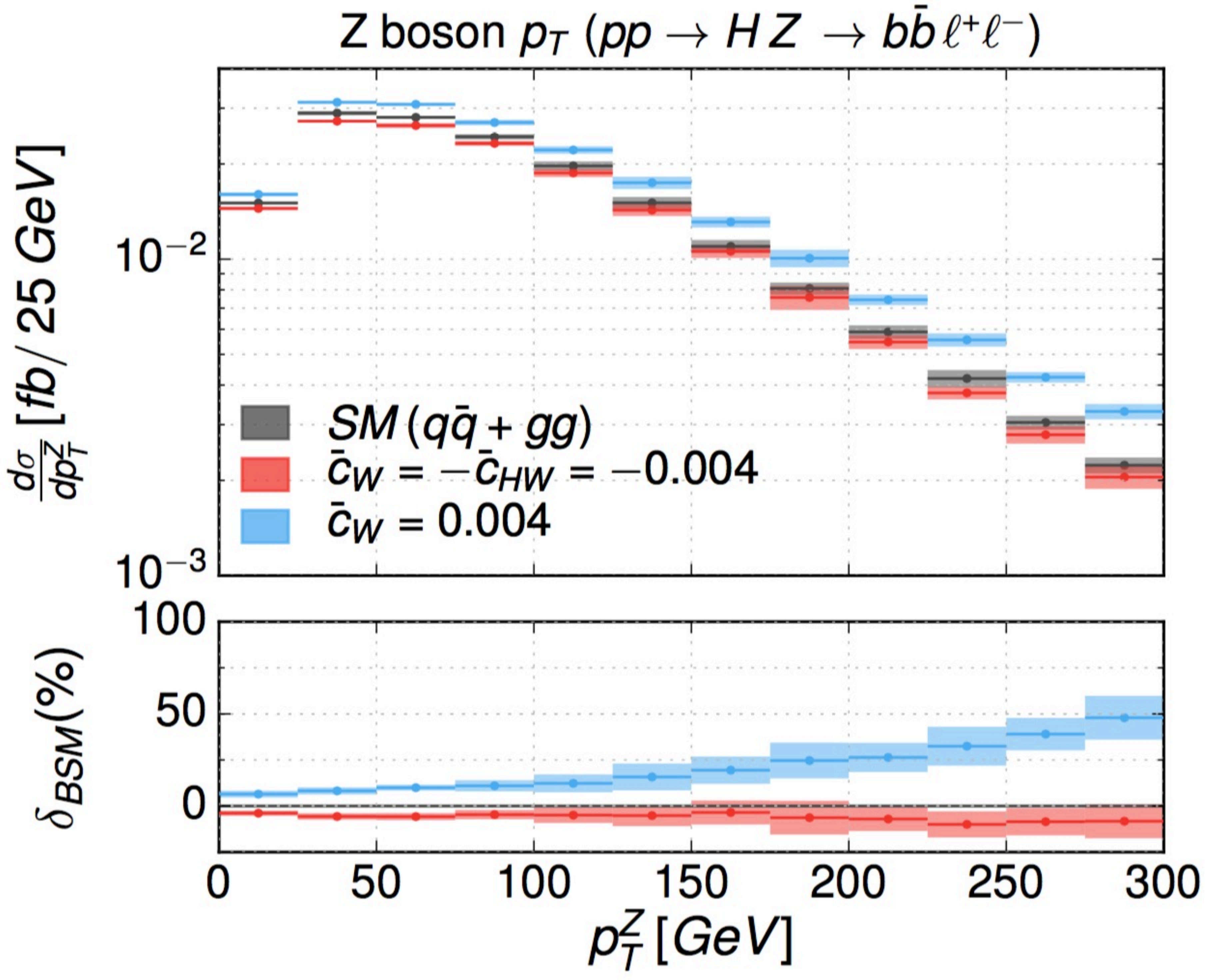
See e.g.
Biekötter, Knochel, Krämer, Liu, Riva,
arXiv:1406.7320



In presence of a higher-dim op such as:

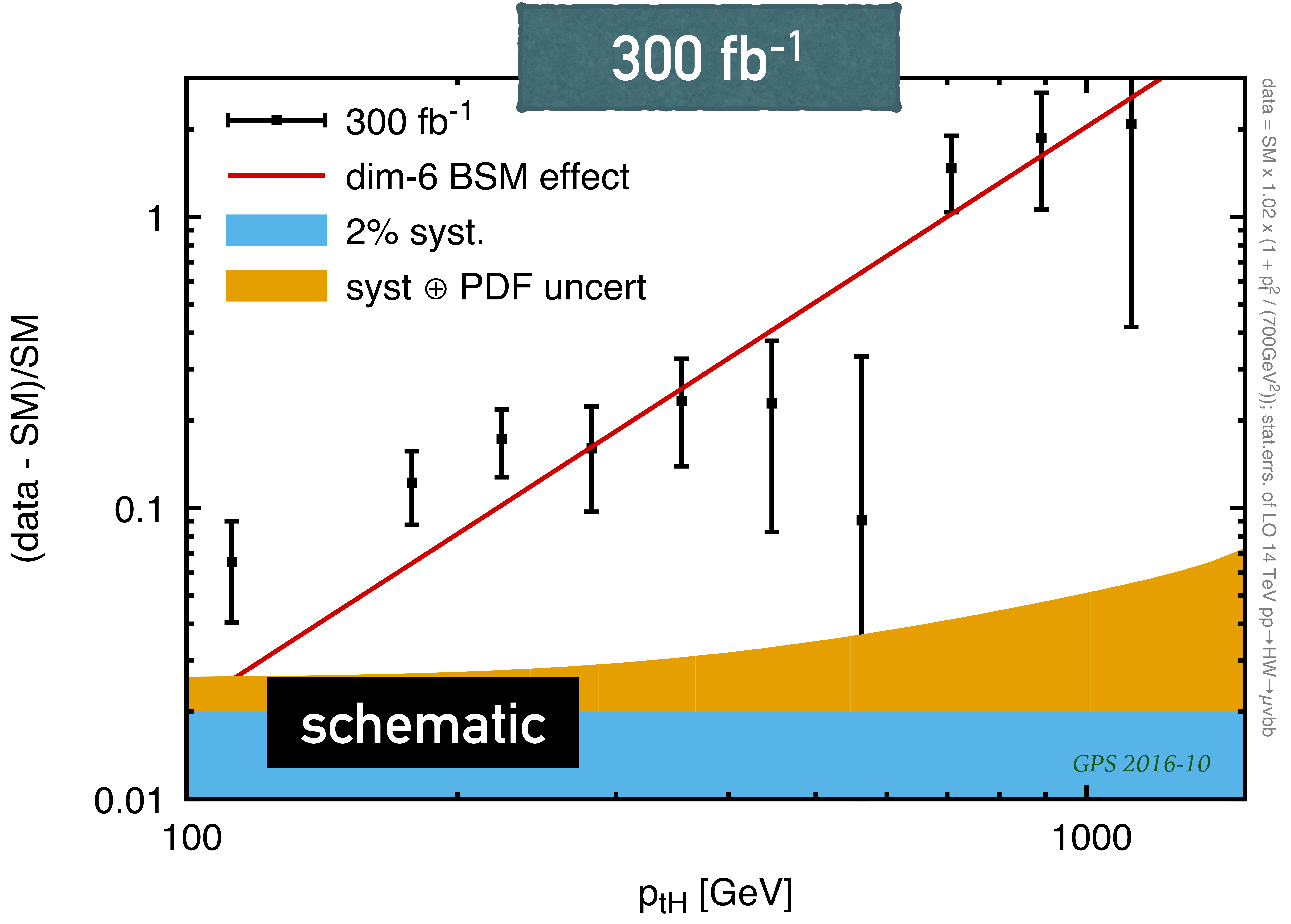
$$L_{D=6} = \frac{ig}{2}\frac{c_W}{\Lambda^2}\left(H^\dagger \sigma^a D^\mu H\right) D^\nu V^a_{\mu\nu}$$

$$\frac{\sigma}{\sigma_{SM}} \sim \left(1 + c_W \frac{\hat{s}}{\Lambda^2}\right)^2$$

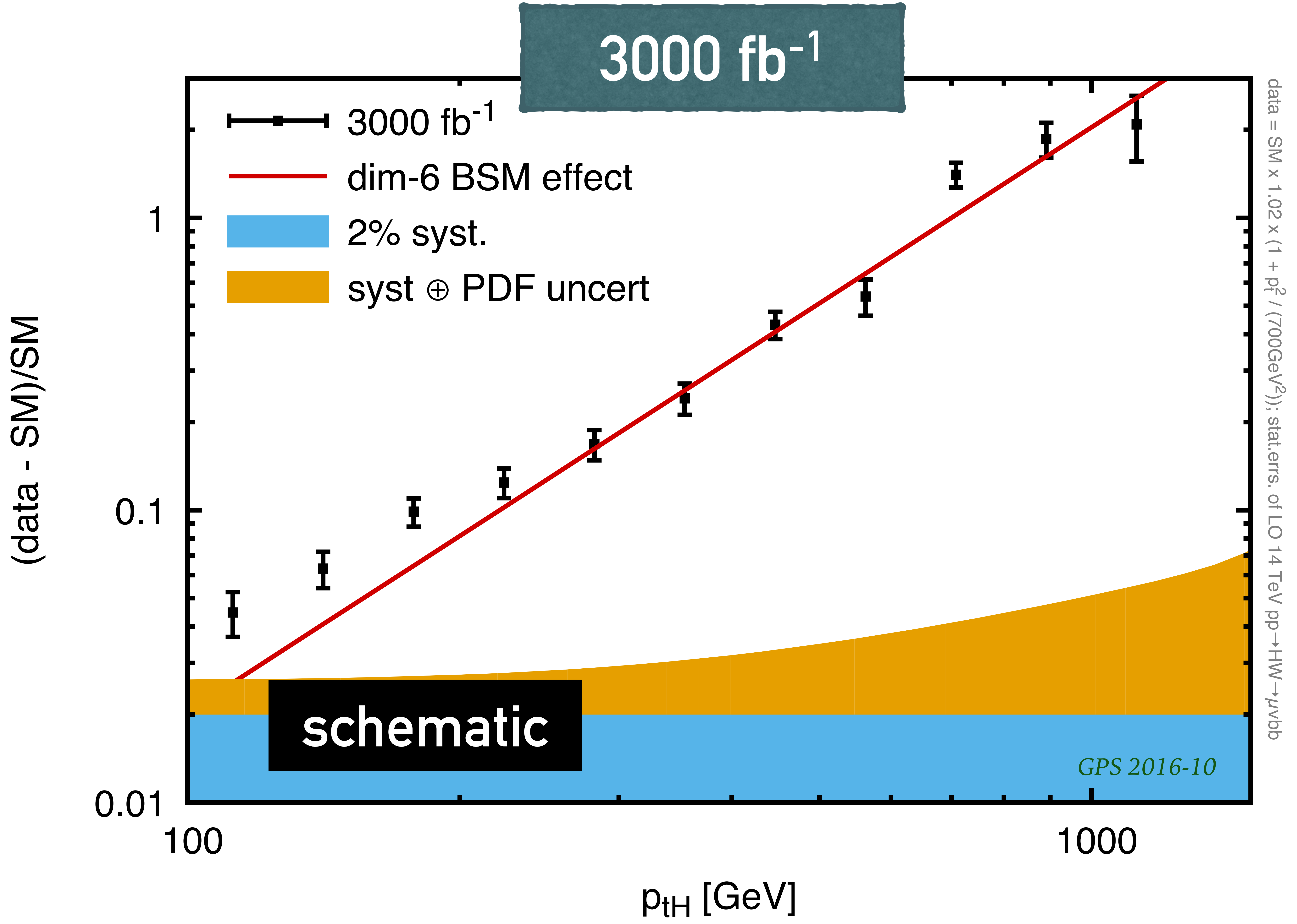


Mimasu, Sanz, Williams, arXiv:1512.02572v

WH at large Q^2 with dim-6 BSM effect



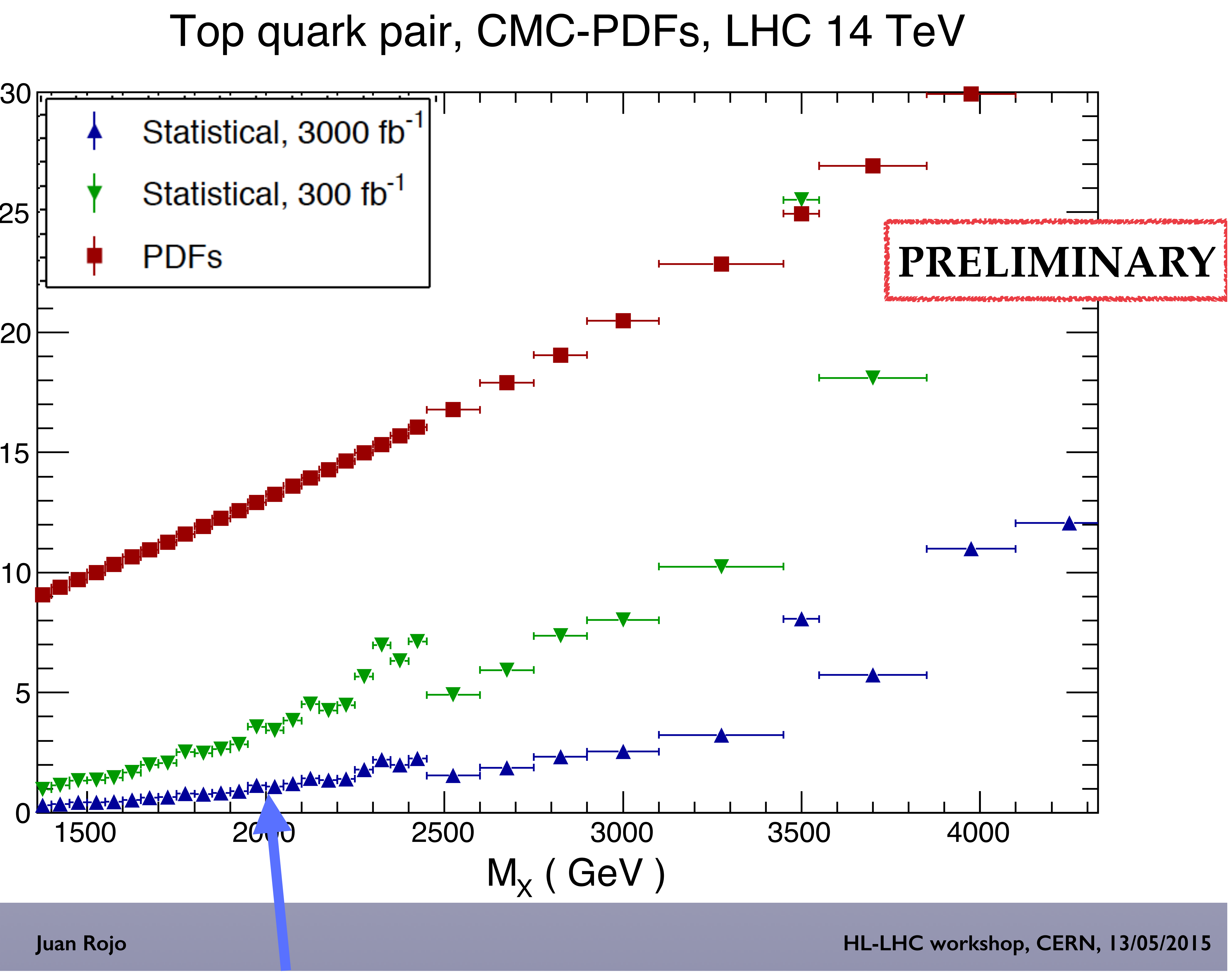
WH at large Q^2 with dim-6 BSM effect



new physics isn't just a single number that's wrong (think g-2)

but rather a distinct scaling pattern of deviation ($\sim p_T^2$)

moderate and high p_T's have similar statistical significance — so it's useful to understand whole p_T range



At HL-LHC, Statistical errors on ttbar production will be < 1% up to M_{tt} ~ 2 TeV

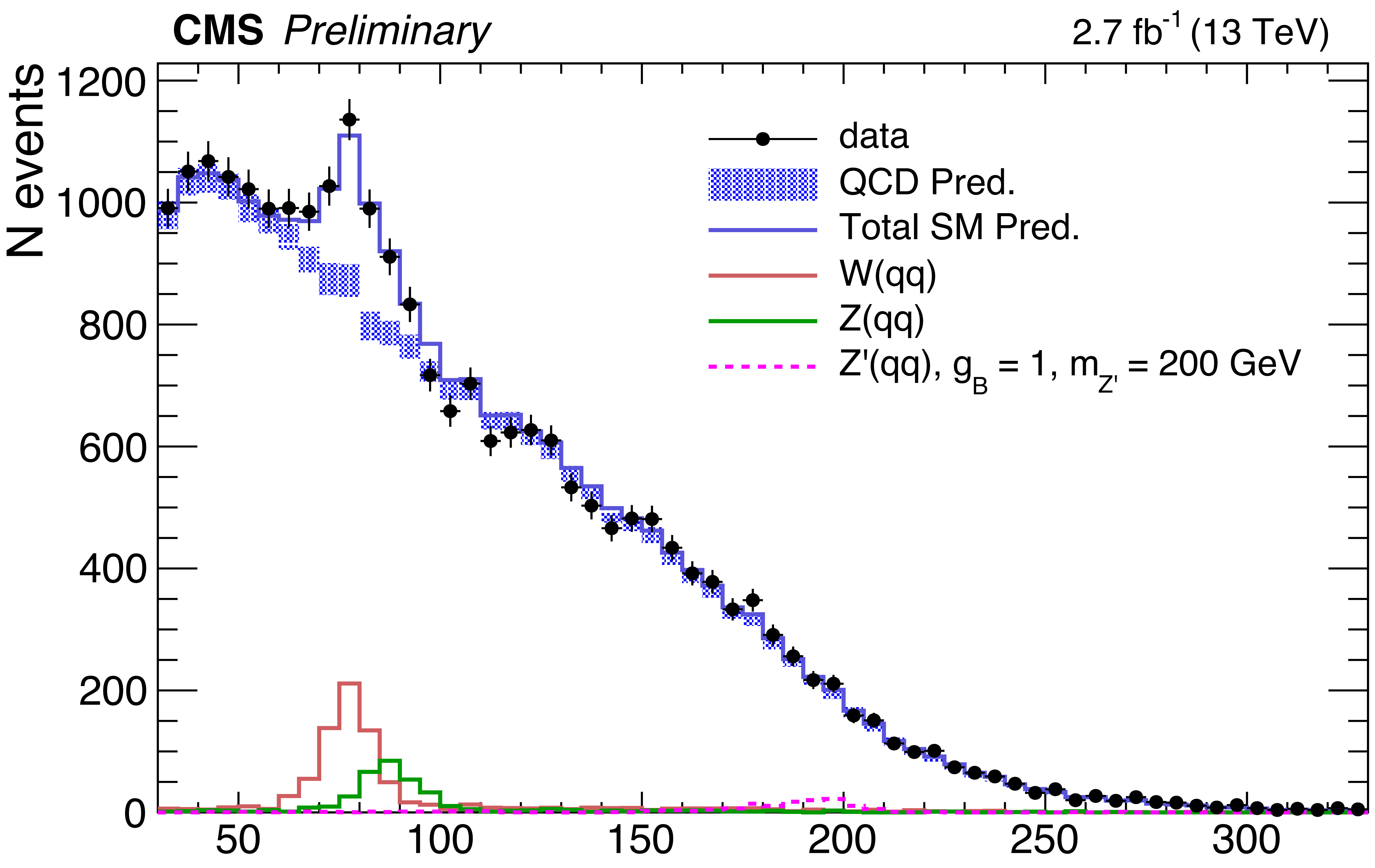
IN THE FUTURE?

- high-pt W, Z
- high-mass Drell-Yan
- high-mass ttbar

Will all be at ~1% statistical level up to and even beyond the TeV scale.

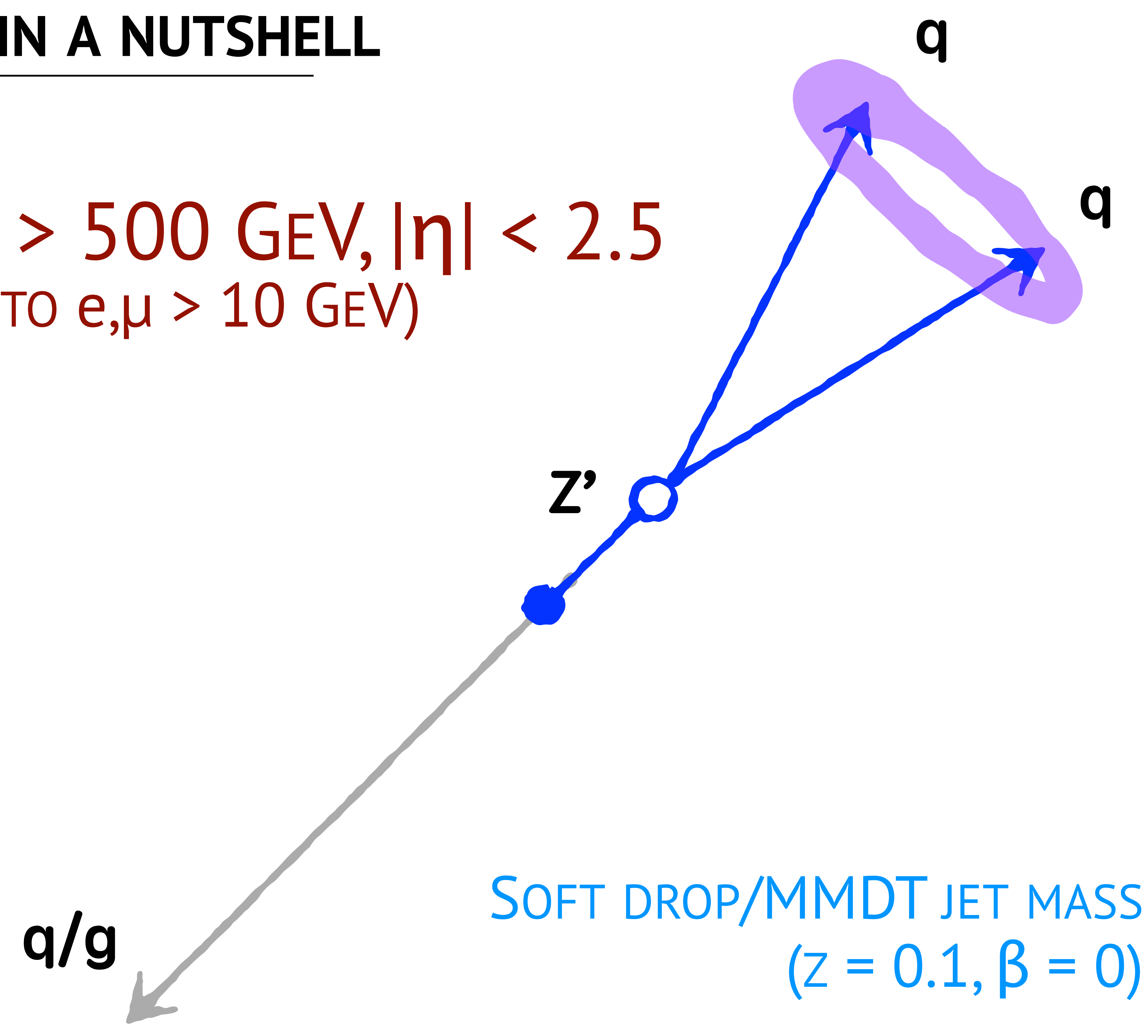
With leptonic final states, there's a chance systematic errors may also be < 1%.

The potential of jet substructure — hadronic W & Z peaks



IN A NUTSHELL

p_T > 500 GeV, $|\eta| < 2.5$
(veto e,μ > 10 GeV)



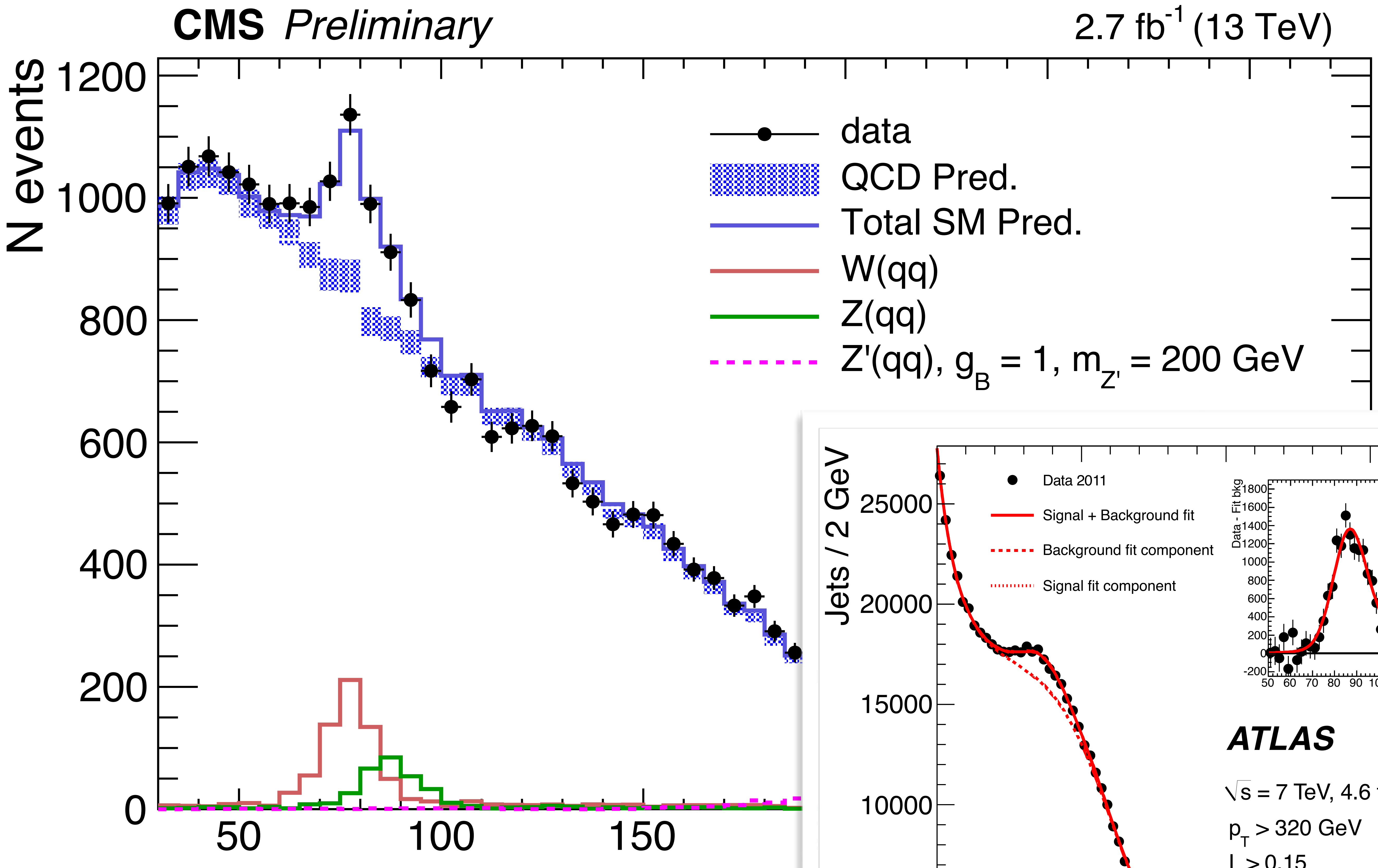
Soft drop/MMDT jet mass
($z = 0.1, \beta = 0$)

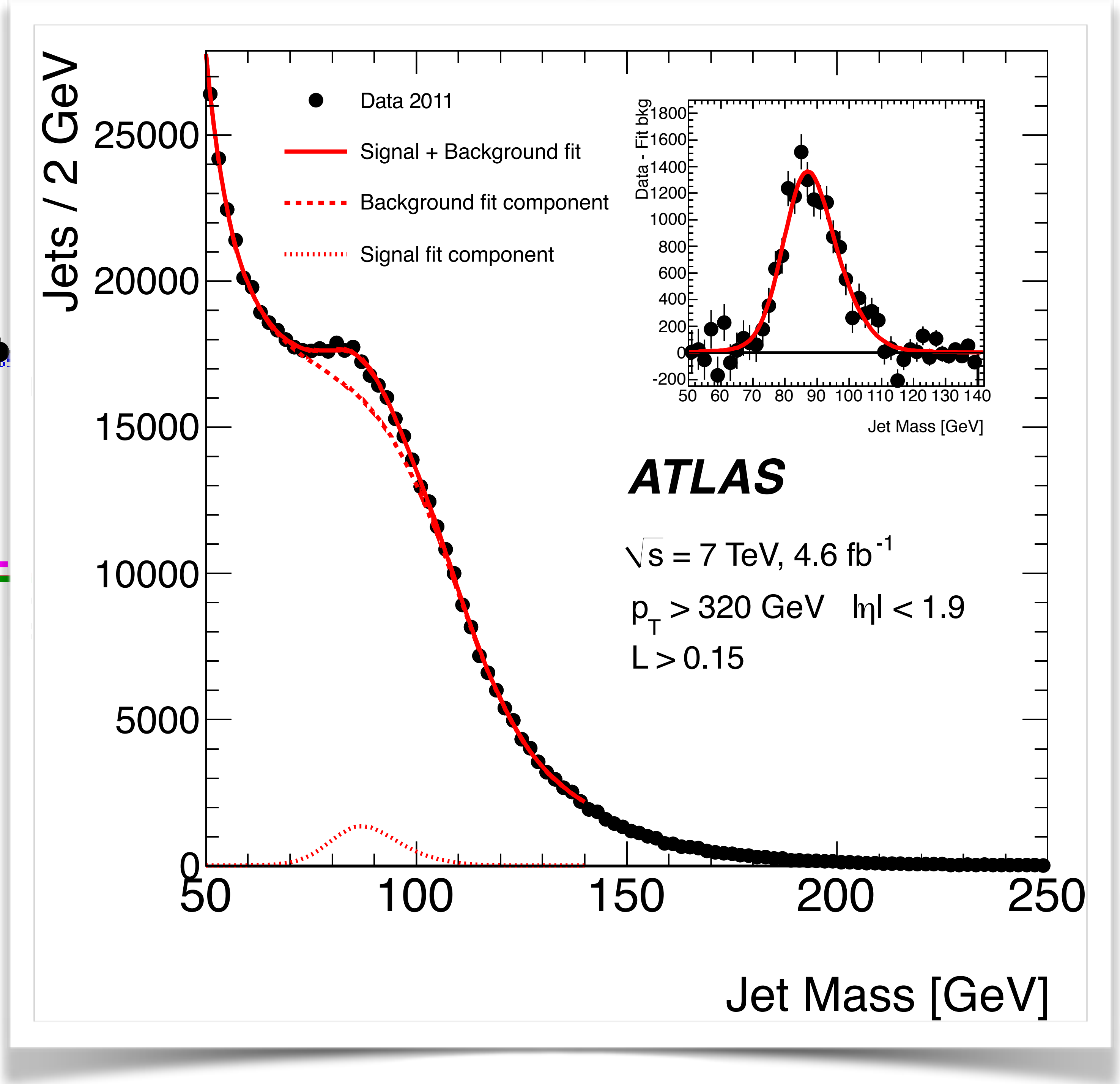
$\tau_{21}^{DDT} < 0.38$

[PUPPI'ed inputs]

Nhan Tran @ Boost 2016

The potential of jet substructure — hadronic W & Z peaks

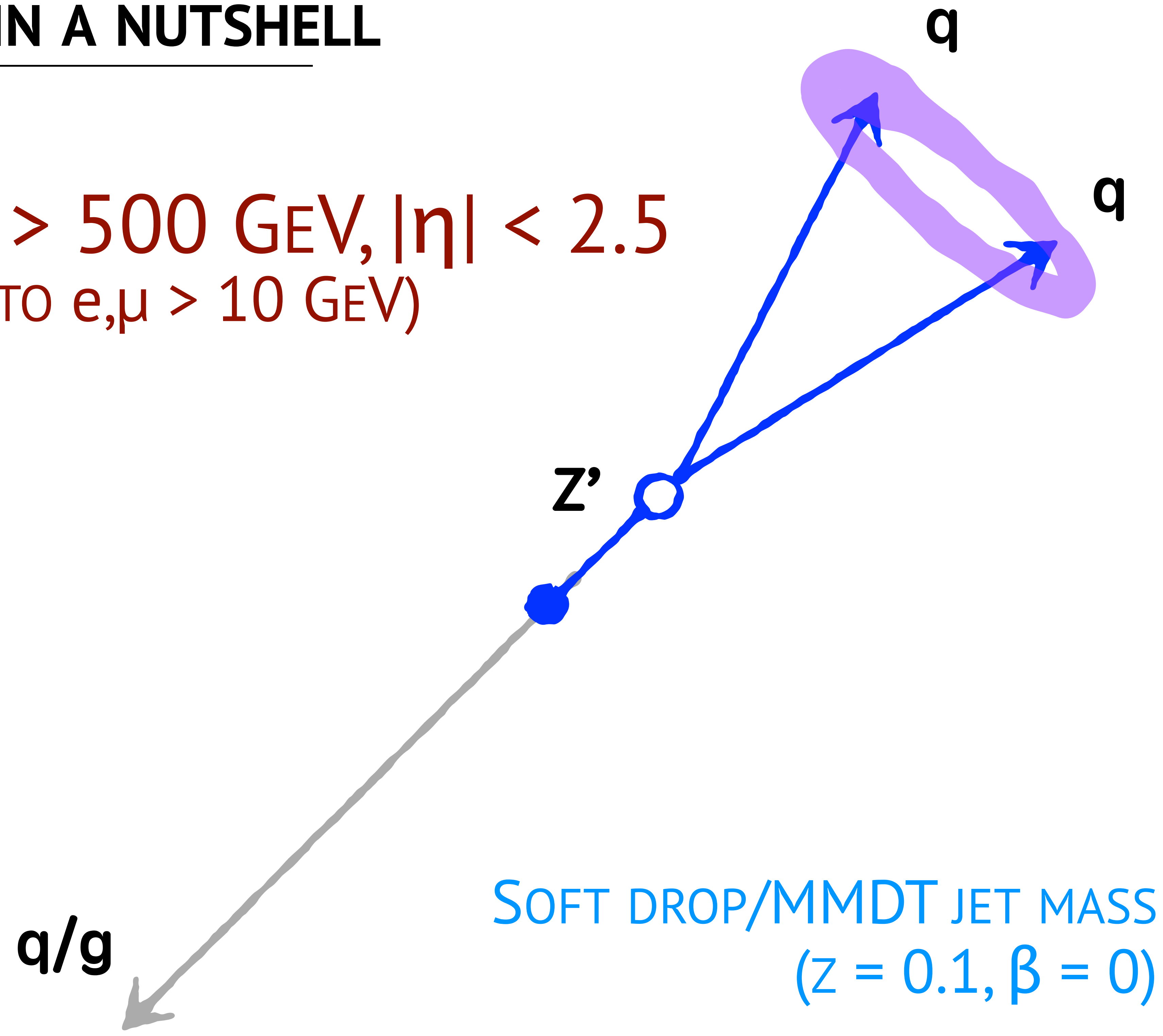




Nhan Tran @ Boost 2016

IN A NUTSHELL

P_T > 500 GeV, $|\eta| < 2.5$
(veto e,μ > 10 GeV)

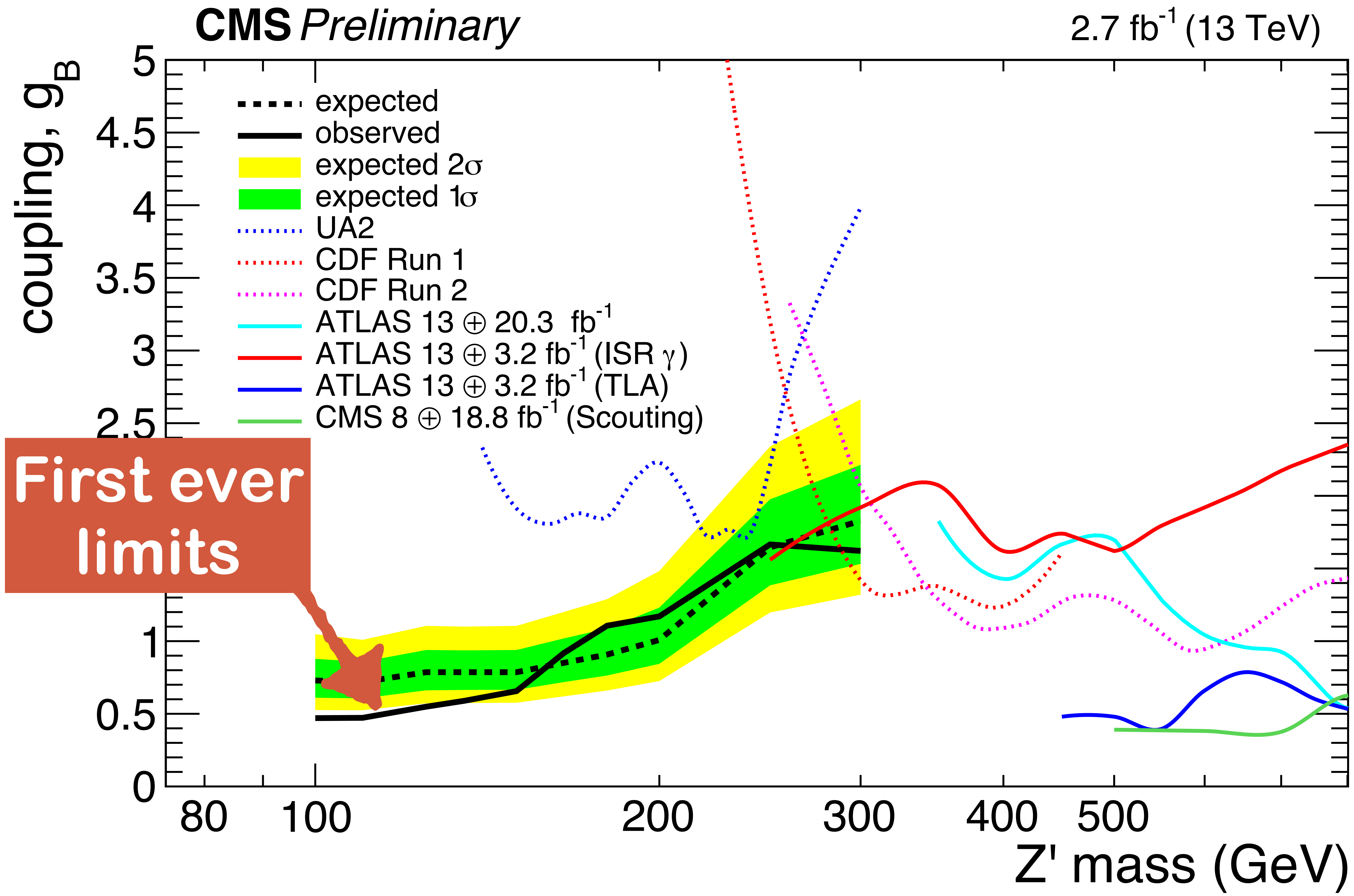


Soft drop/MMDT jet mass
($z = 0.1, \beta = 0$)

$\tau_{21}^{DDT} < 0.38$

[PUPPI'ed inputs]

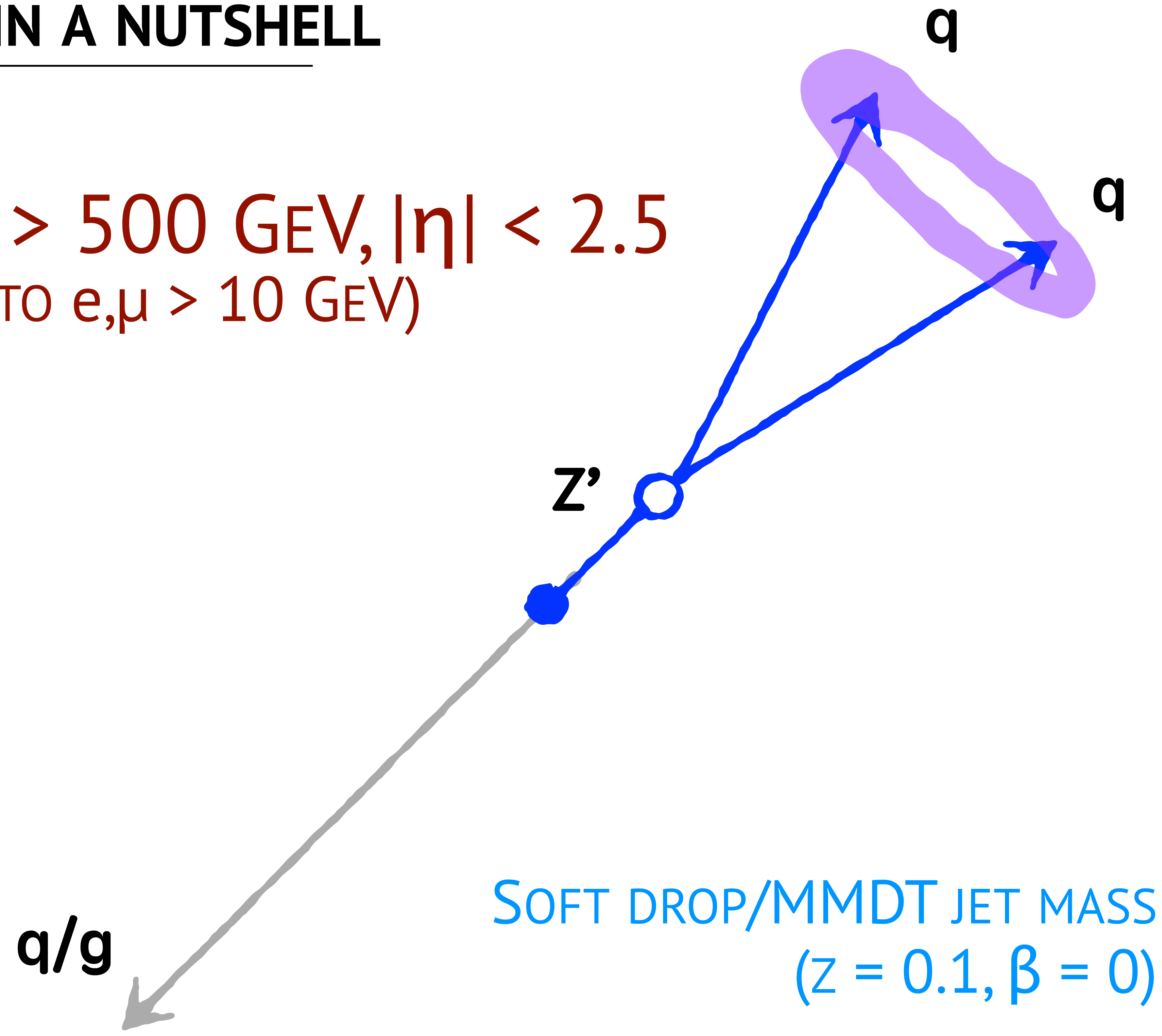
The potential of jet substructure — hadronic W & Z peaks



Nhan Tran @ Boost 2016

IN A NUTSHELL

P_T > 500 GeV, $|\eta|$ < 2.5
(veto e,μ > 10 GeV)



Soft drop/MMDT jet mass
(z = 0.1, β = 0)

$\tau_{21}^{DDT} < 0.38$

[PUPPI'ed inputs]

outlook

MESSAGES

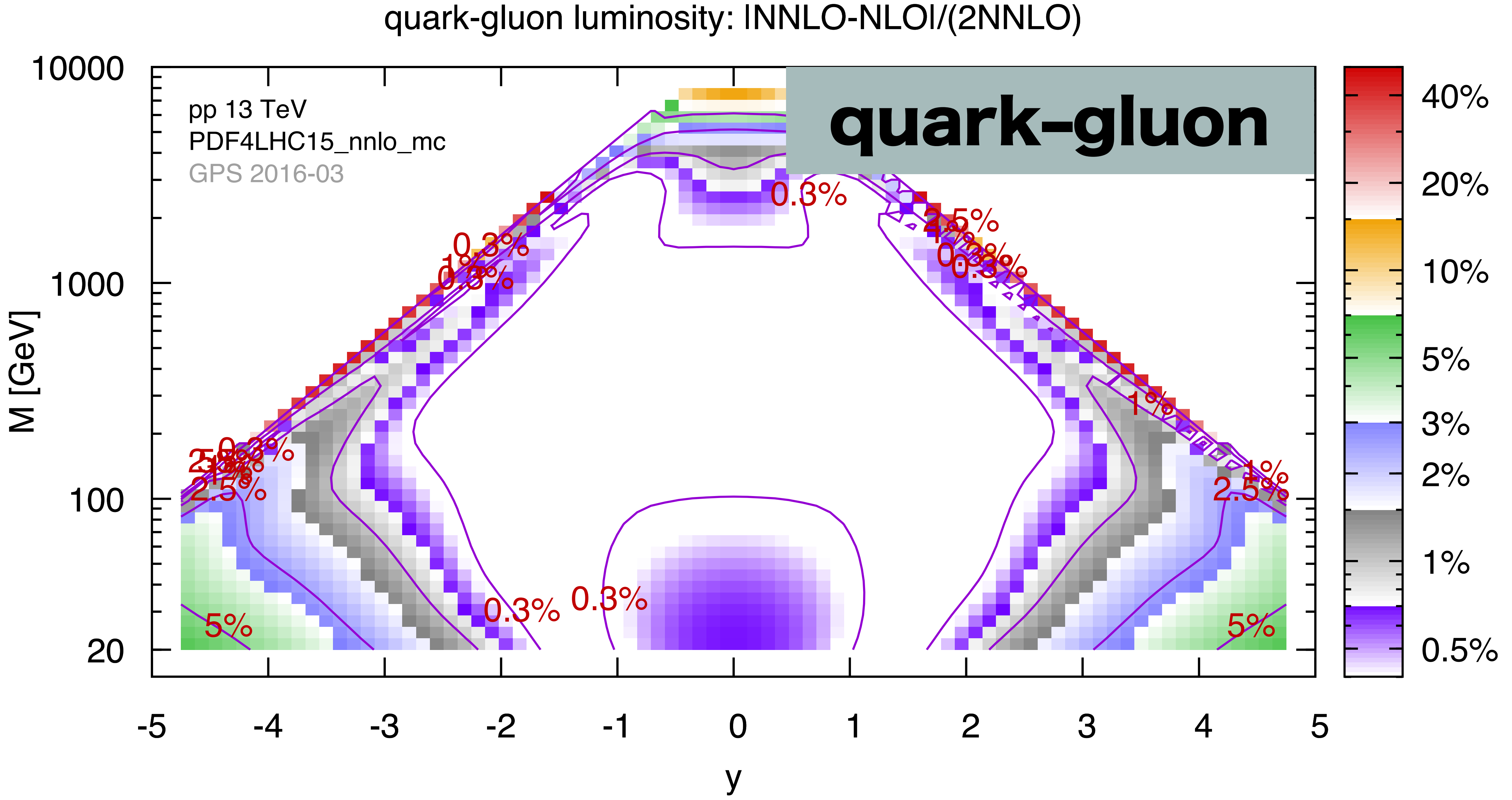
- Higgs sector is unlike any other that we've worked with experimentally
- Testing its structure is a key part of our job as physicists

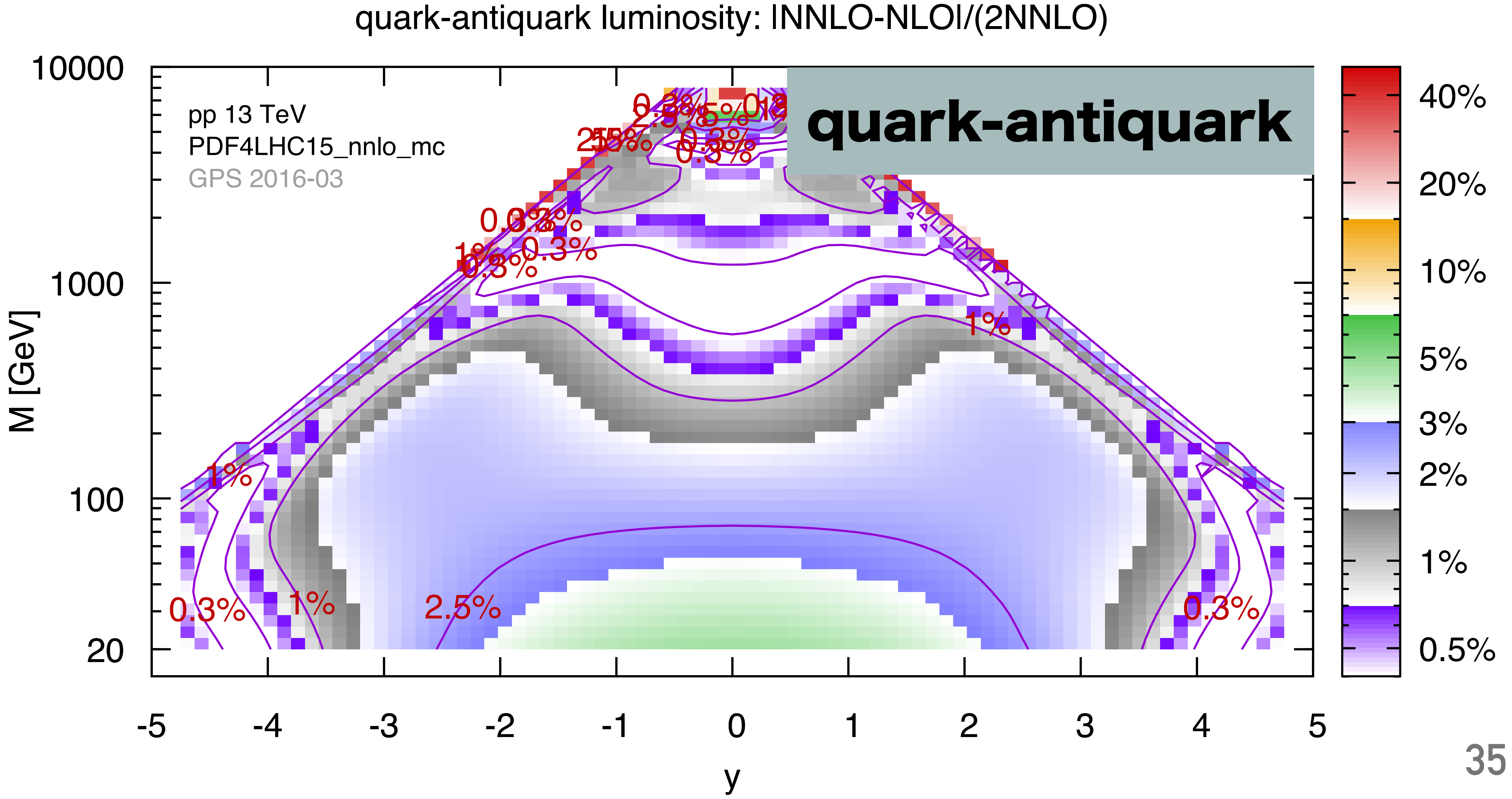
- One element in testing it is **precision**
  - Theory is already making big steps towards the HL-LHC precision goals
  - Ultimate goal might be O(1%) — challenging, but now is time to start thinking about how we get there (PDF fits, exp. lumi determination, etc.)
- Other element is **distributions, e.g. high-p_T**
  - BSM effects from high scales (Λ) grow ~ p_T^2 / Λ^2
  - Growth can help evade systematic limits & provide clear signature of new physics

EXTRA SLIDES

PDF THEORY UNCERTAINTIES

Theory Uncertainties

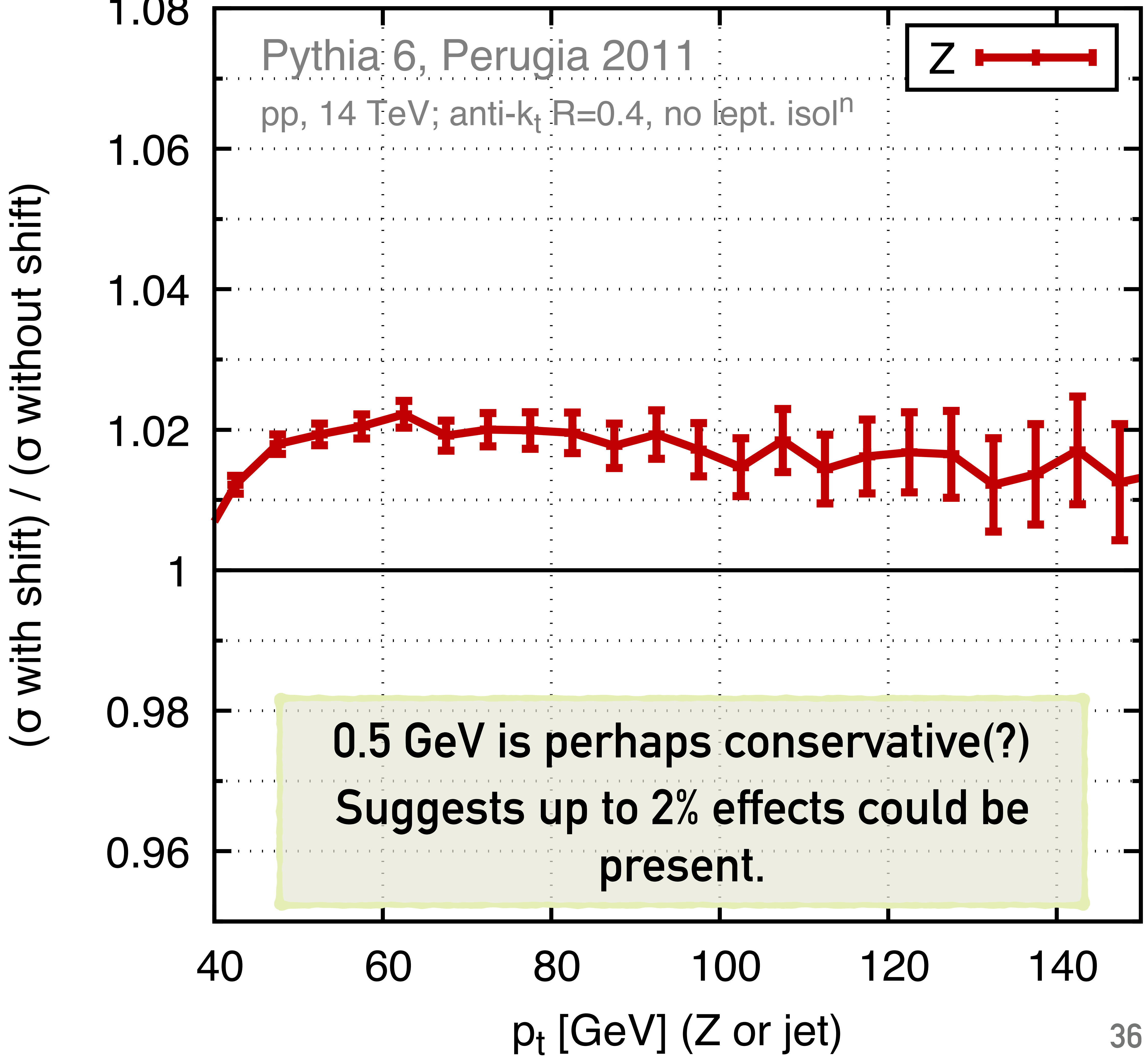




Non-perturbative effects in Z (& H?) p_T

- Inclusive Z & H cross sections should have $\sim\Lambda^2/M^2$ corrections ($\sim 10^{-4}$?)
- Z (&H) p_T **not inclusive** so corrections can be $\sim\Lambda/M$.
- Size of effect can't be probed by turning MC hadronisation on/off
  [maybe by modifying underlying MC parameters?]
- Shifting Z p_T by a finite amount illustrates what could happen

impact of 0.5 GeV shift of Z p_T



PRECISION LHC PHYSICS NEEDS PRECISION THEORY

Progress on calculations has been stunning in the past years

- N3LO Higgs
- Many processes at NNLO
- NLO + PS automation
- First NNLO + PS
- NNLL Resummations
- EW + QCD, etc.

This progress is essential for LHC precision physics, but also only part of the story.

PRECISION LHC PHYSICS NEEDS PRECISION THEORY

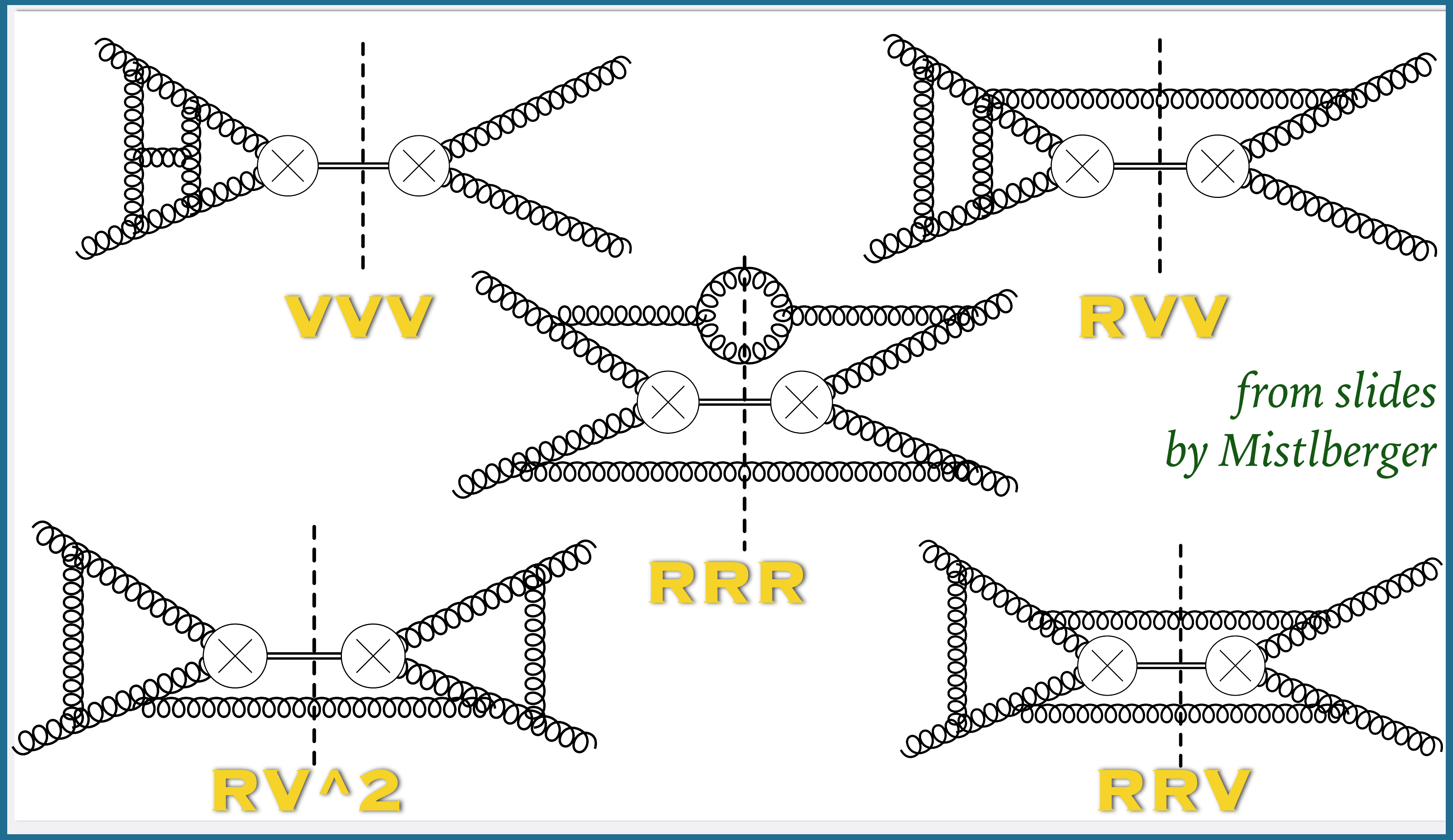
Progress on calculations has been stunnin

- ➤ N3LO Higgs
- ➤ Many processes at NNLO
- ➤ NLO + PS automation
- ➤ First NNLO + PS
- ➤ NNLL Resummations
- ➤ EW + QCD, etc.

N3LO Higgs production

Anastasiou, Duhr, Dulat, Herzog, Mistlberger ’15-16

100,000 diagrams



PRECISION LHC PHYSICS NEEDS PRECISION THEORY

Progress on calculations has been stunning in the past years

- N3LO Higgs
- Many processes at NNLO
- NLO + PS automation
- First NNLO + PS
- NNLL Resummations
- EW + QCD, etc.

This progress is essential for LHC precision physics, but also only part of the story.

The intention with this talk?

Start asking questions about what precision goals we might set ourselves, what obstacles we will meet, what techniques and measurements might help us progress

REFS

- ATLAS projections ATL-PHYS-PUB-2014-016
- CMS projections (snowmass): 1307.7135

- Current status — ATLAS/CMS combination note

- YR4 14 TeV numbers: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt14TeV
- YR3 14 TeV numbers: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt1314TeV2014#s_14_0_TeV
- new ggF https://arxiv.org/abs/1602.00695
- ATLAS differential 1504.05833, CMS differential: ZZ 1512.08377 & gg 1508.07819

HIGGS TODAY & TOMORROW

Production process	ATLAS+CMS
μ_{ggF}	$1.03^{+0.17}_{-0.15}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$

Decay channel	ATLAS+CMS
$\mu^{\gamma\gamma}$	$1.16^{+0.20}_{-0.18}$
μ^{ZZ}	$1.31^{+0.27}_{-0.24}$
μ^{WW}	$1.11^{+0.18}_{-0.17}$
$\mu^{\tau\tau}$	$1.12^{+0.25}_{-0.23}$
μ^{bb}	$0.69^{+0.29}_{-0.27}$

ATLAS-CMS Run I combination

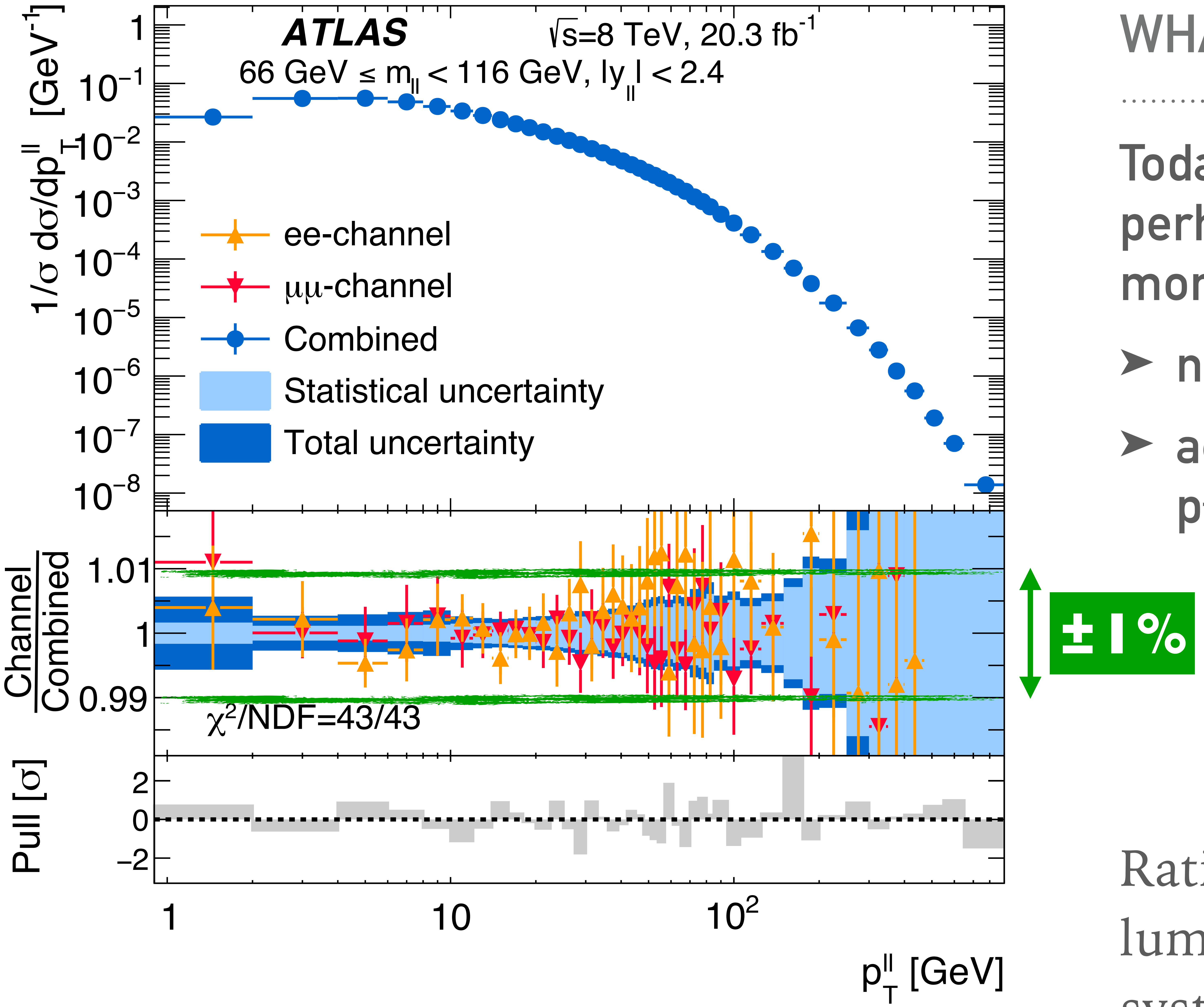
In most cases, stat. errors are largest single source

Best channels $\sim\pm 20\%$

HL-LHC prospects?

x2.5 in cross section
x150 in luminosity (→ 3000 fb^{-1})
~ 400 times more events

⇒ stat. errors in 1-2% range



WHAT'S POSSIBLE EXPERIMENTALLY?

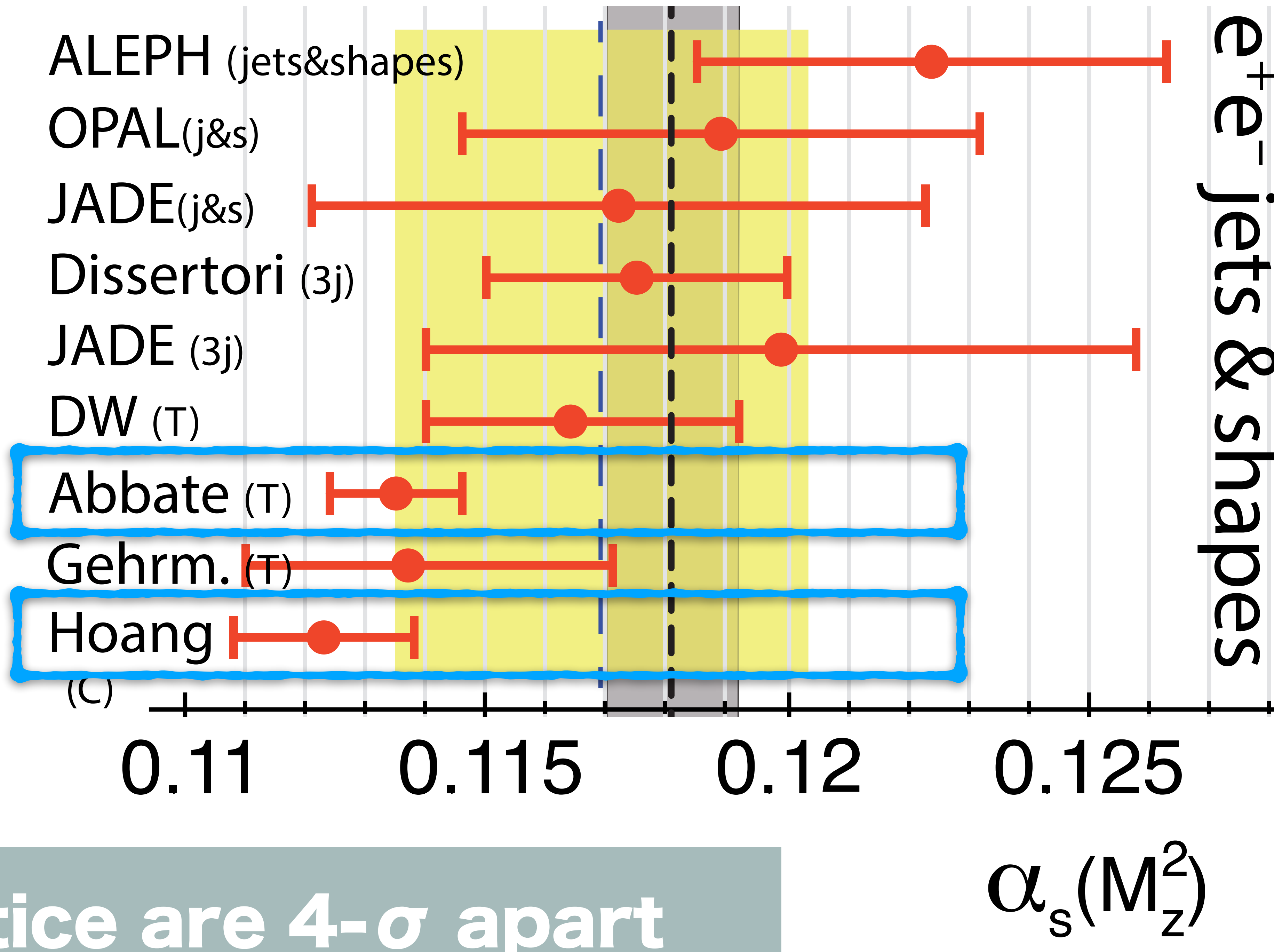
Today's most precise results are perhaps for the Z transverse momentum

- ➤ normalised to Z fiducal σ
- ➤ achieves <1%, from p_T = 1 to 200 GeV

Ratio to total cross section cancels lumi & some lepton-efficiency systematics.

E+E- EVENT SHAPES AND JET RATES

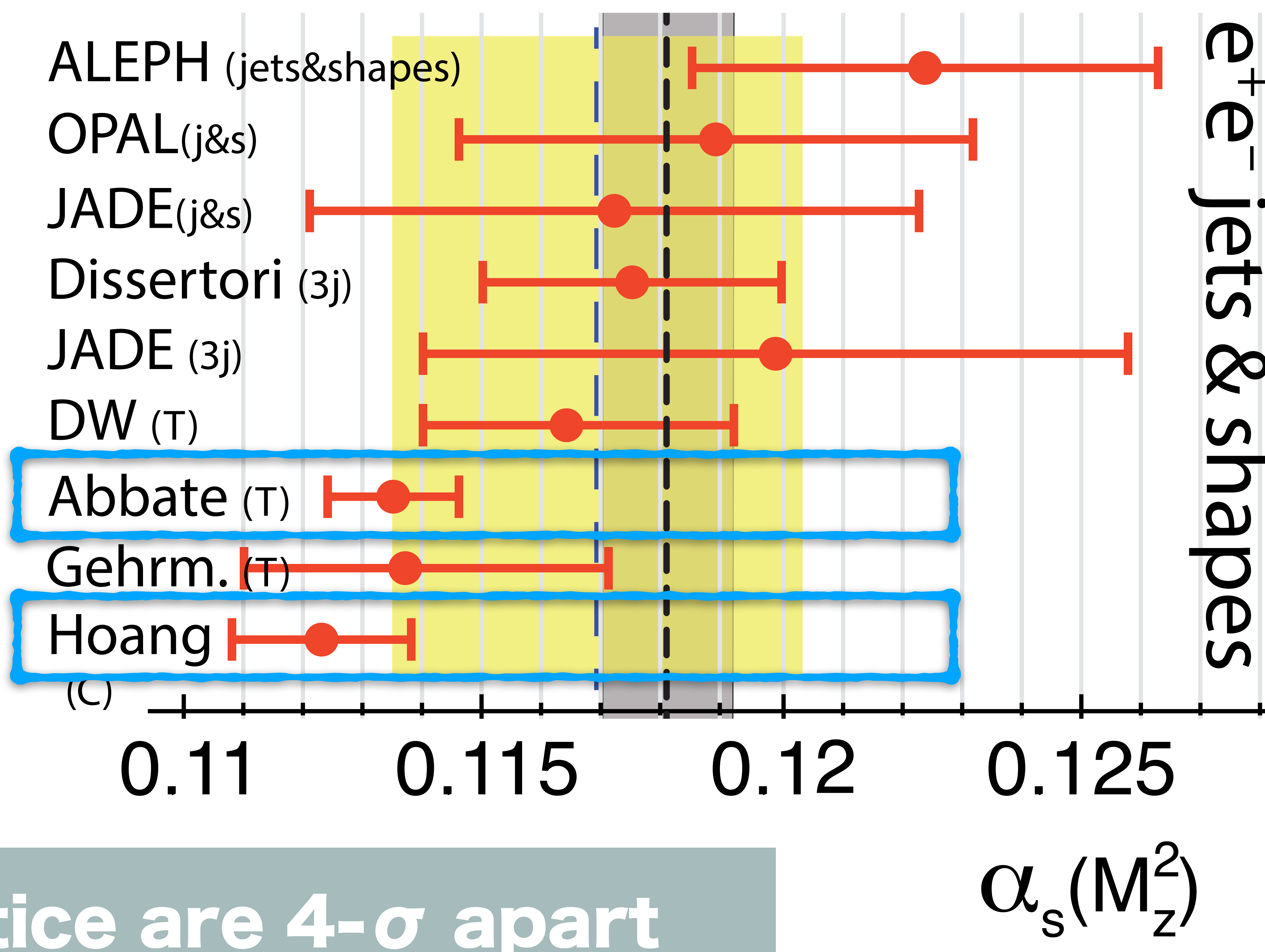
➤ Two "best" determinations are from same group (Hoang et al, 1006.3080,1501.04111)
$\alpha_s(M_Z) = 0.1135 \pm 0.0010$ (0.9%) [thrust]
$\alpha_s(M_Z) = 0.1123 \pm 0.0015$ (1.3%) [C-parameter]



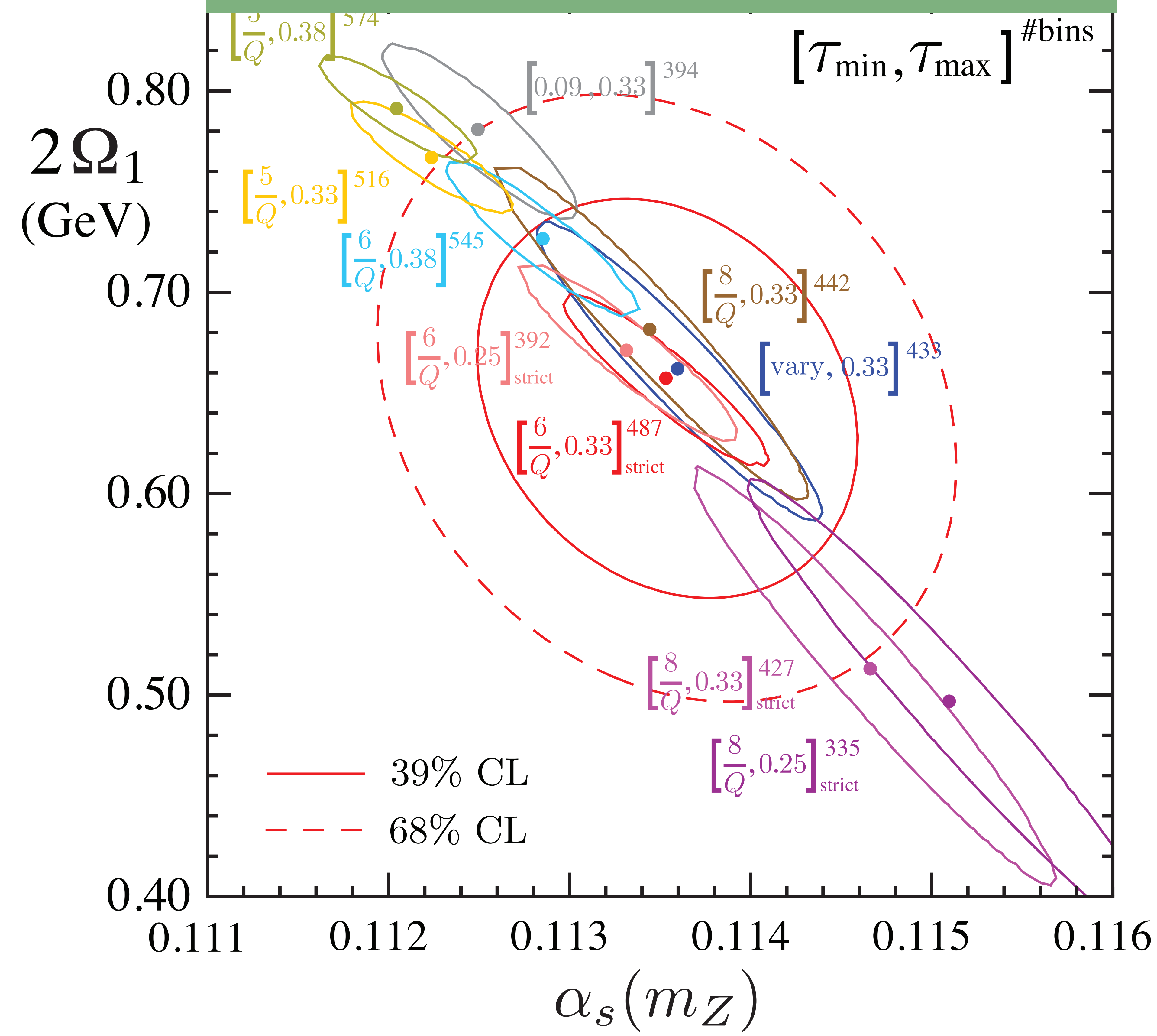
thrust & "best" lattice are 4-σ apart

E+E- EVENT SHAPES AND JET RATES

- Two "best" determinations are from same group
  (Hoang et al, 1006.3080,1501.04111)
  $\alpha_s(M_Z)$ = 0.1135 ± 0.0010 (0.9%) [thrust]
  $\alpha_s(M_Z)$ = 0.1123 ± 0.0015 (1.3%) [C-parameter]



dependence on fit range



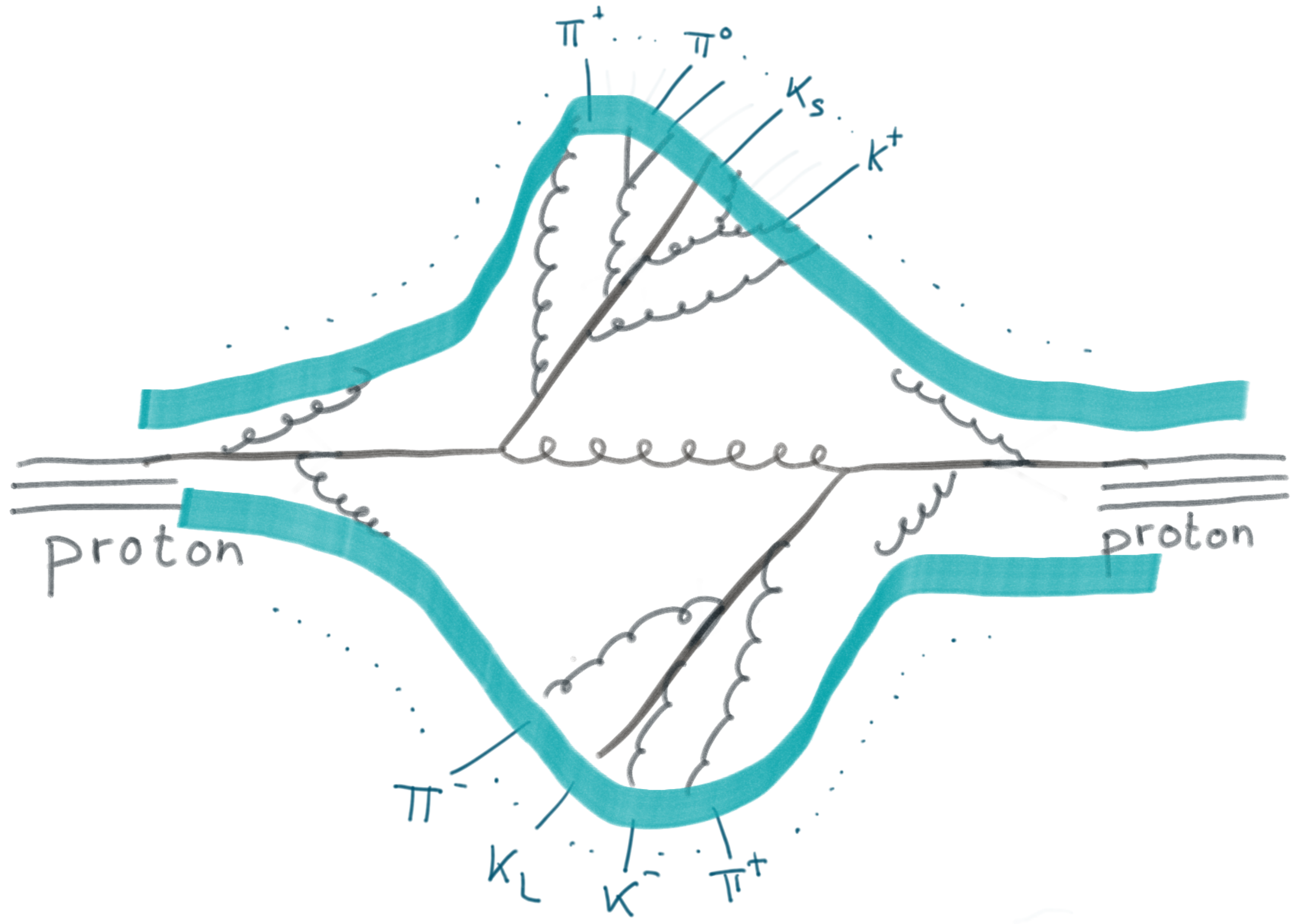
thrust & "best" lattice are 4-σ apart

Comments:

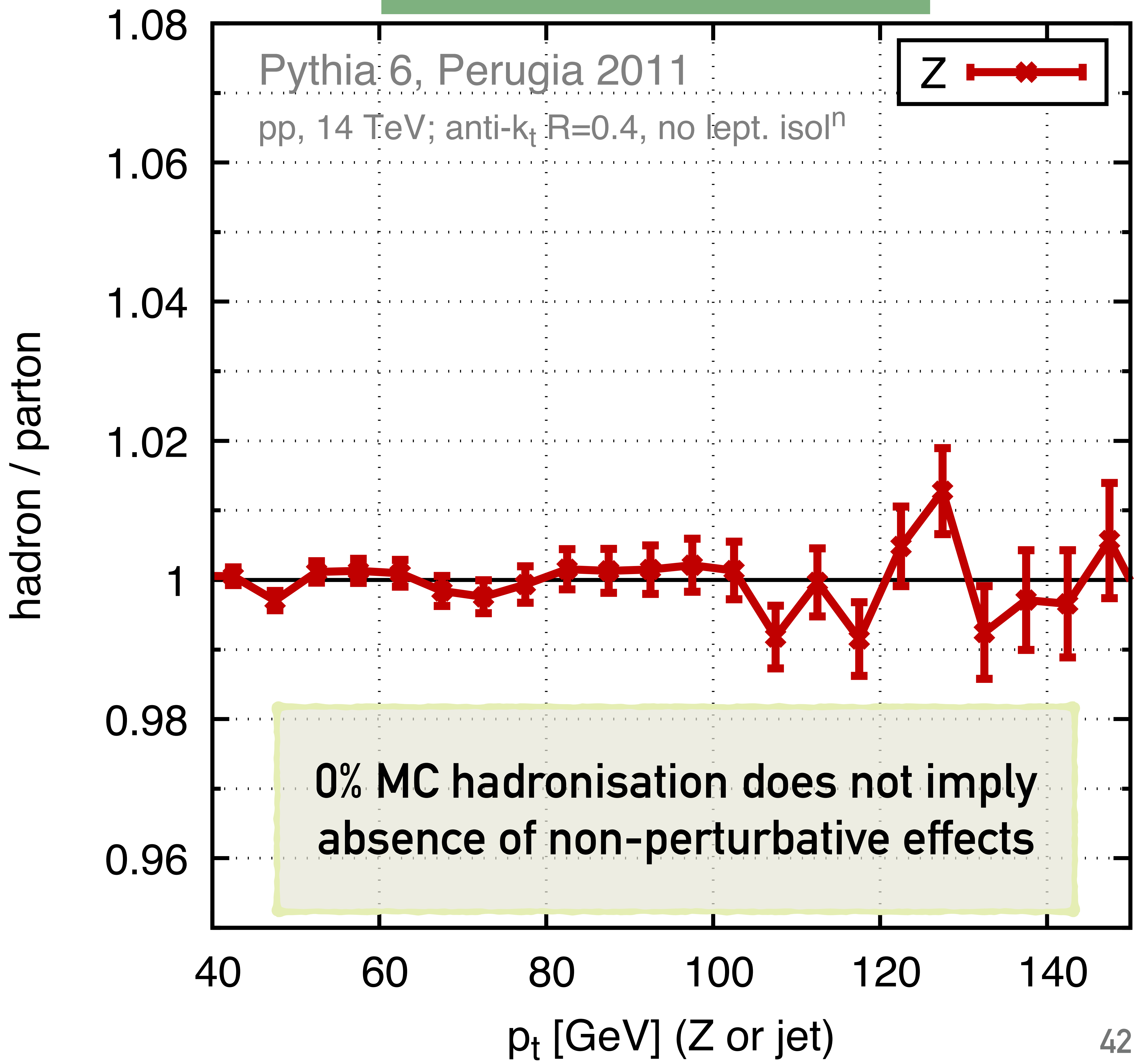
- thrust & C-parameter are highly correlated observables
- Analysis valid far from 3-jet region, but not too deep into 2-jet region — at LEP, not clear how much of distribution satisfies this requirement
- thrust fit shows noticeable sensitivity to fit region (C-parameter doesn't)

Non-perturbative effects in Z p_T

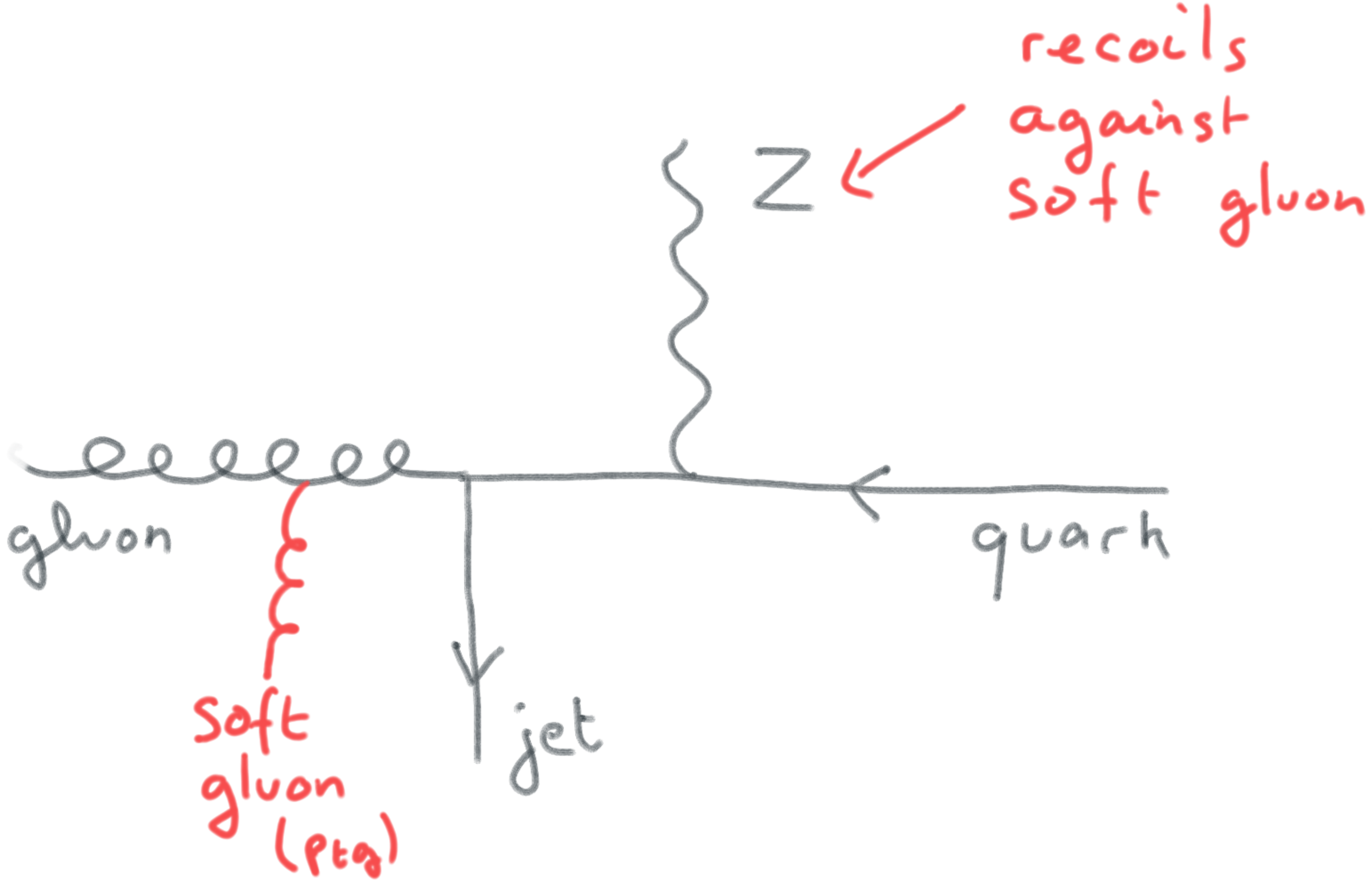
- Inclusive Z cross section should have $\sim\Lambda^2/M^2$ corrections ($\sim 10^{-4}$?)
- Z p_T is **not inclusive** so corrections can be $\sim\Lambda/M$.
- It seems size of effect can't be probed by turning MC hadronisation on/off [maybe by modifying underlying MC parameters?]



MC hadronisation



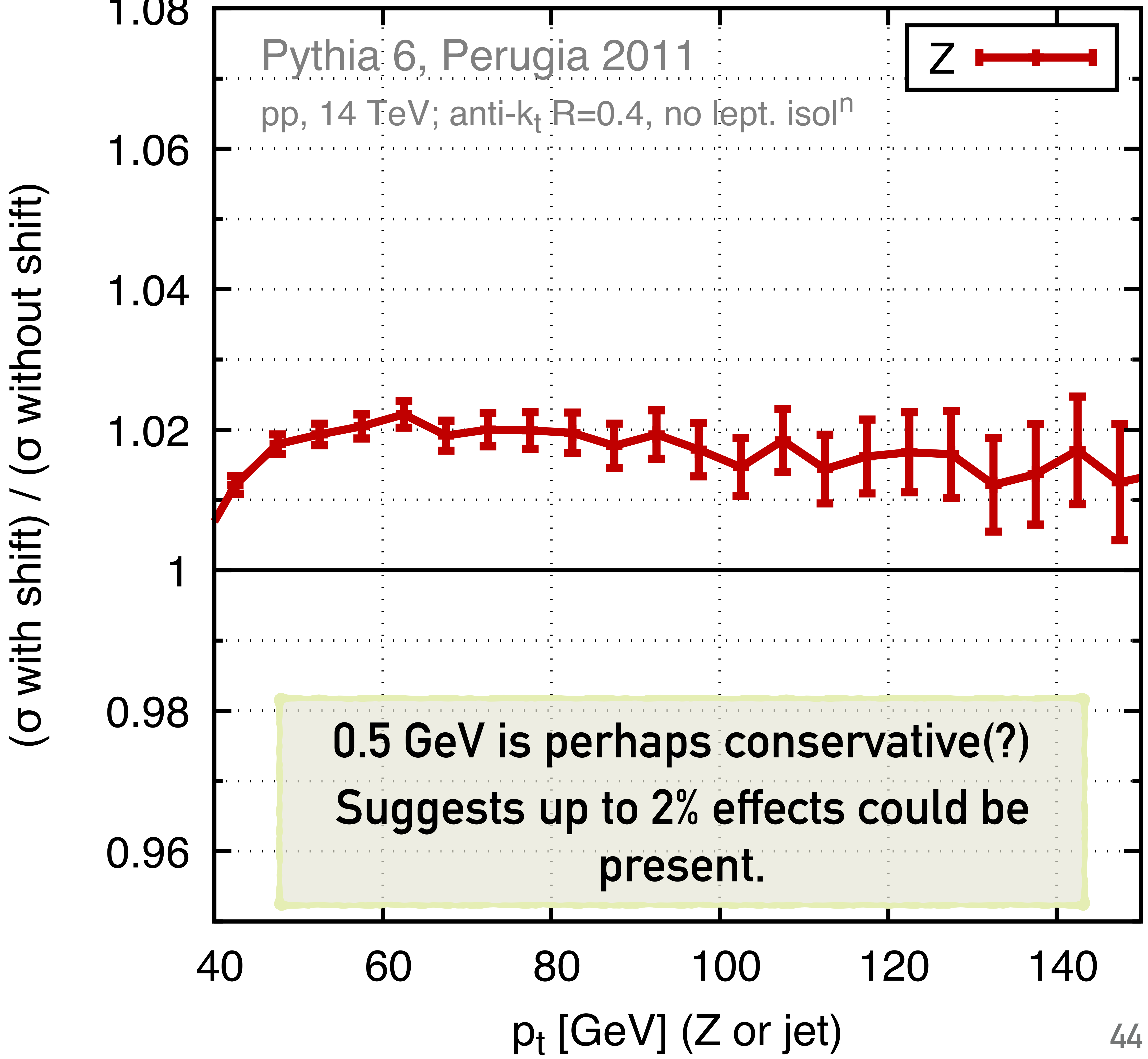
Non-perturbative effects in Z p_T



Non-perturbative effects in Z p_T

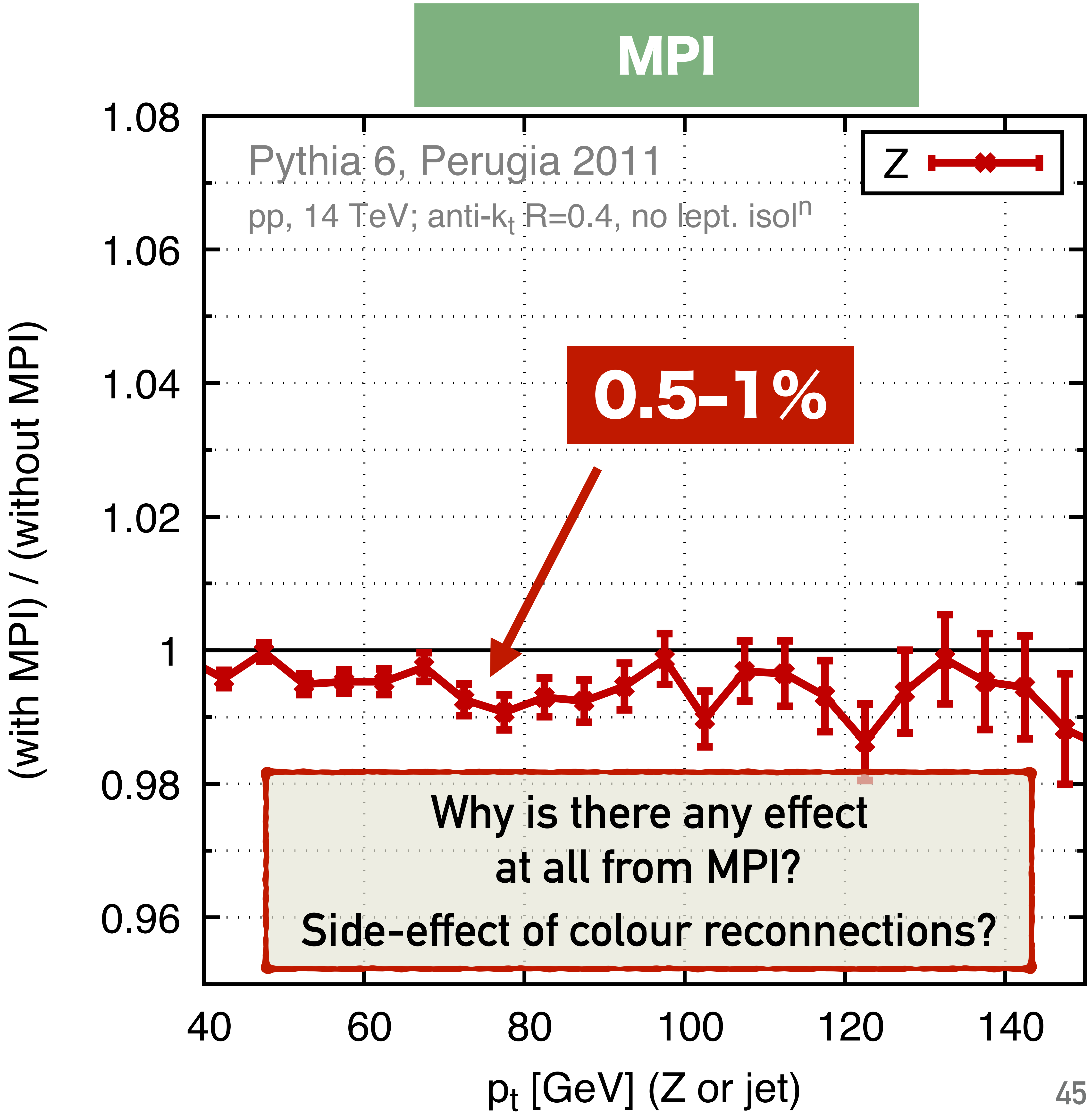
- Inclusive Z cross section should have $\sim\Lambda^2/M^2$ corrections ($\sim 10^{-4}$?)
- Z p_T is **not inclusive** so corrections can be $\sim\Lambda/M$.
- Size of effect can't be probed by turning MC hadronisation on/off
  [maybe by modifying underlying MC parameters?]
- Shifting Z p_T by a finite amount illustrates what could happen

impact of 0.5 GeV shift of Z p_T



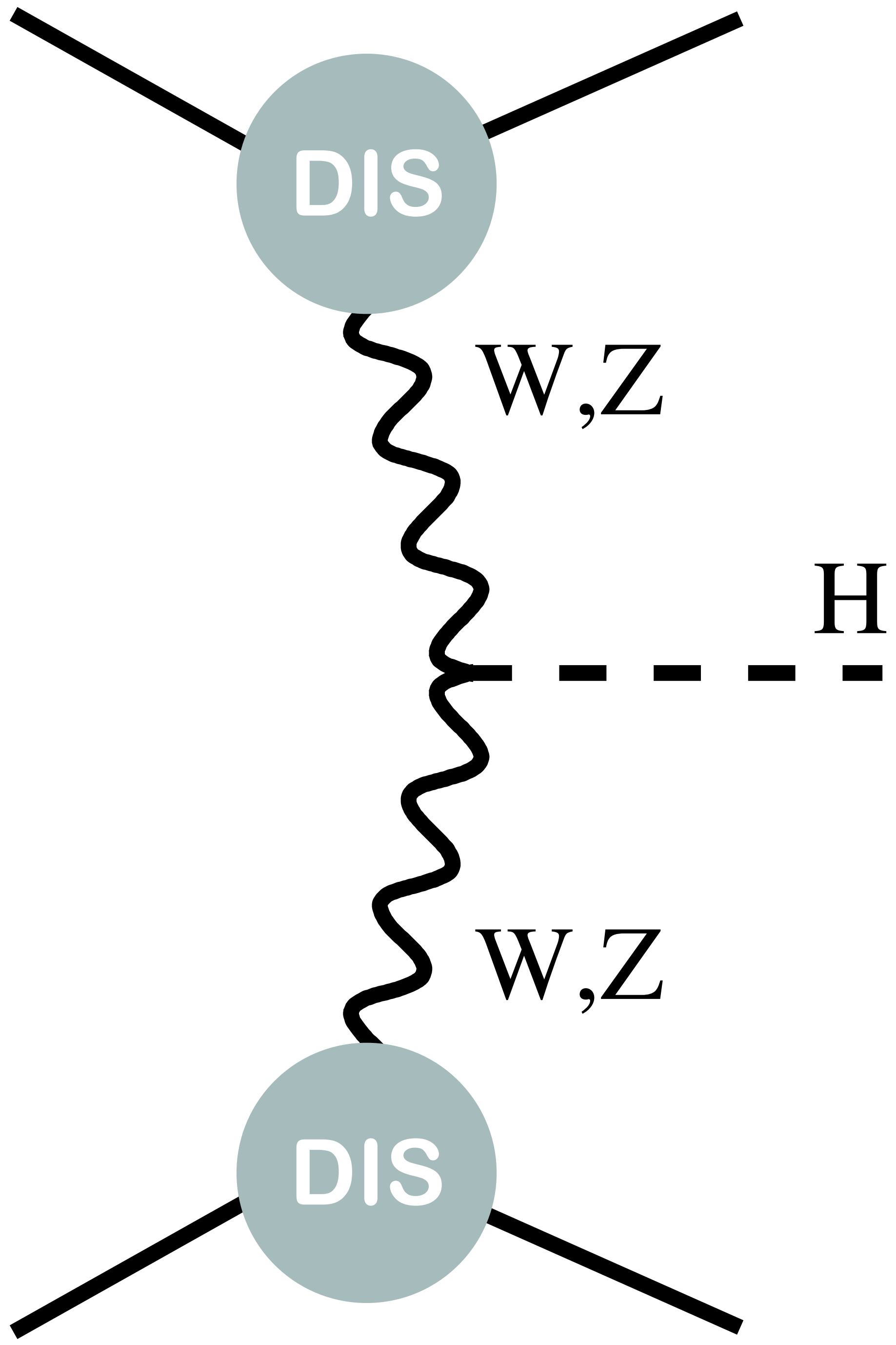
Multi-Parton Interactions?

- Naively, you'd expect these are not correlated with Z p_T — but in at least one MC (Pythia 6) switching them on/off changes distribution by O(1%)

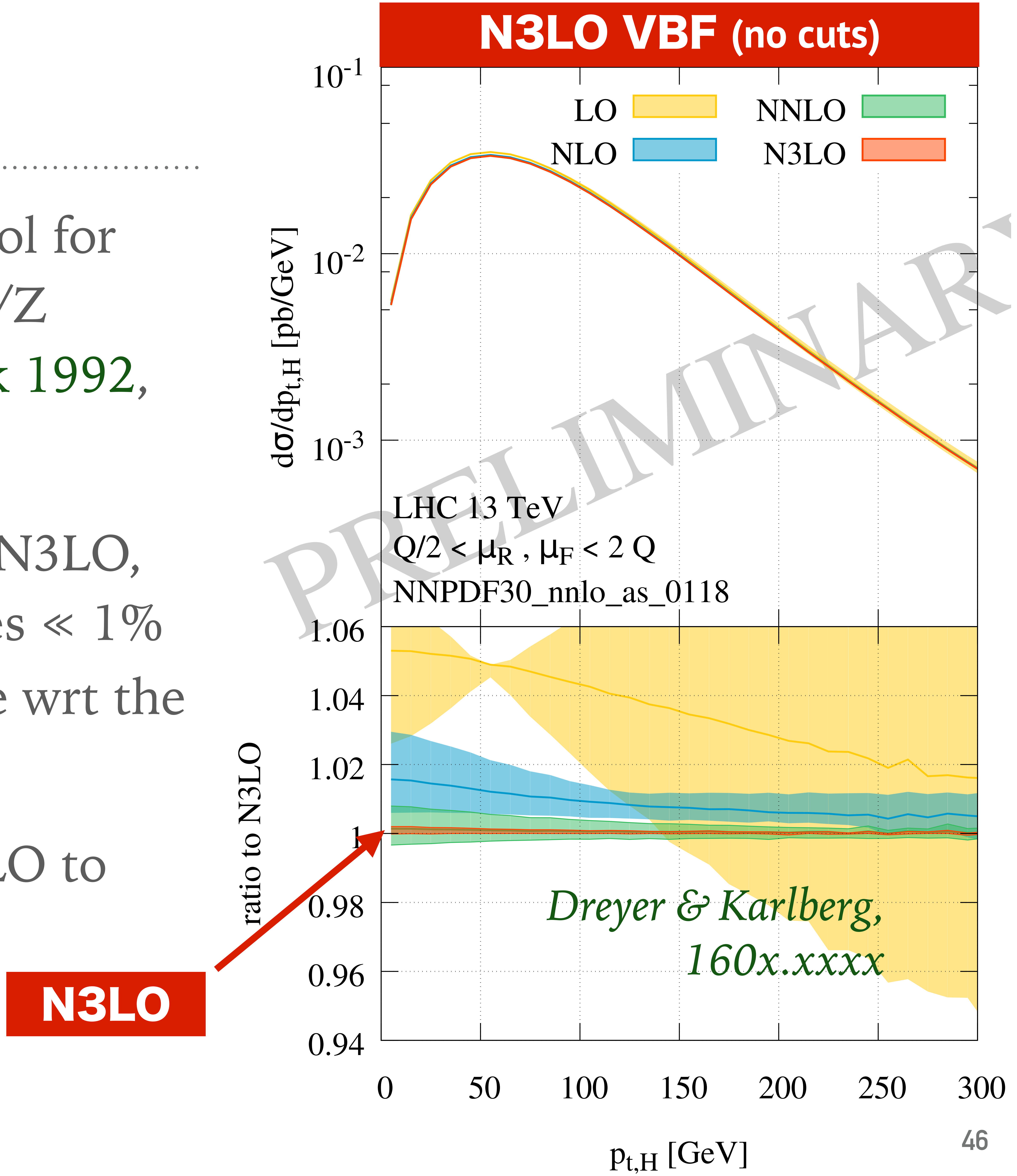


VECTOR-BOSON FUSION → HIGGS

- double DIS approximation is powerful tool for VBF, using structure functions for the W/Z production (Han, Valencia & Willenbrock 1992, NNLO by Bolzoni et al 1003.4451)



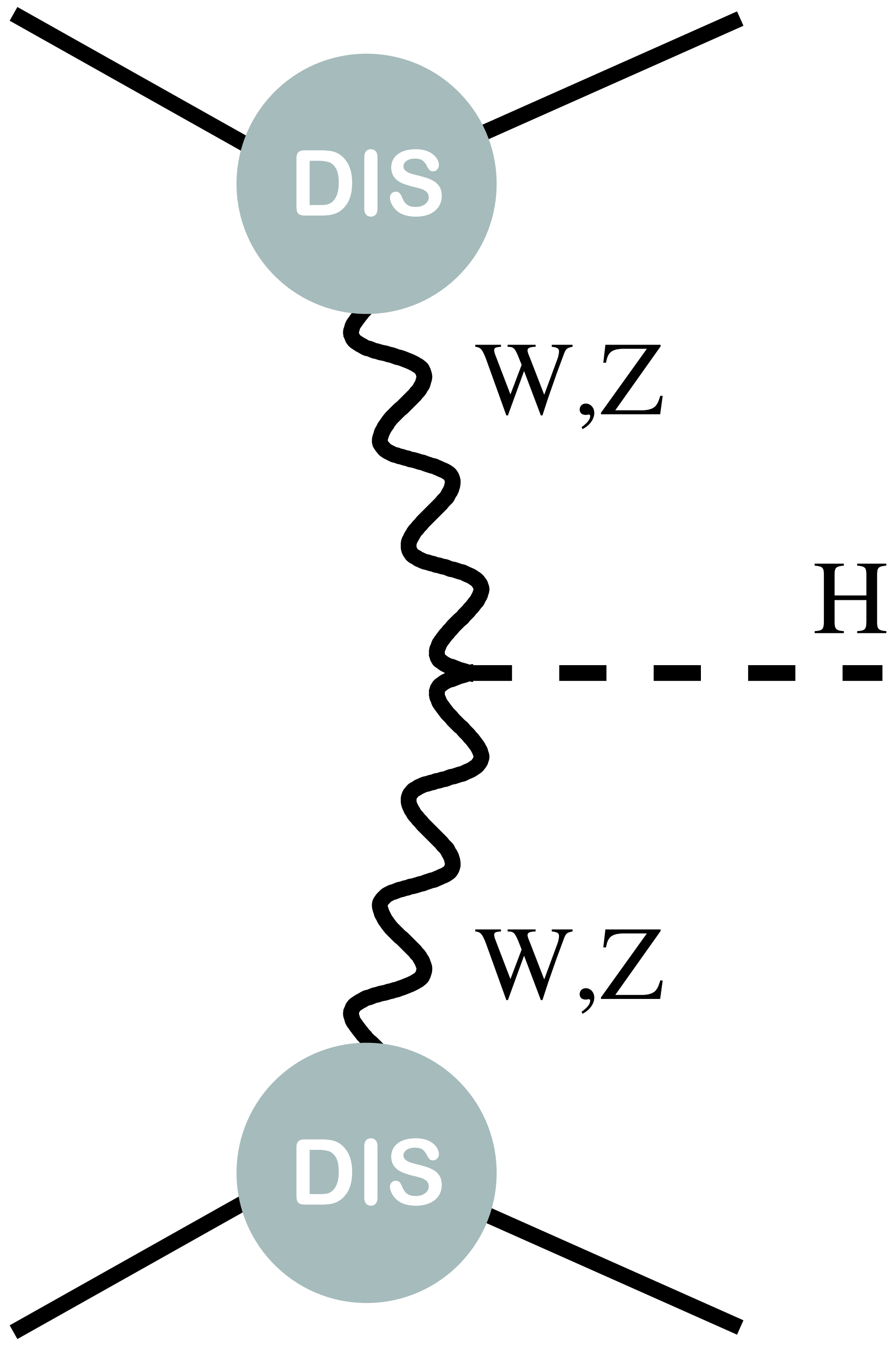
- Now being extended to N3LO, shows scale uncertainties « 1% for observables inclusive wrt the jets
- good stability from NNLO to N3LO



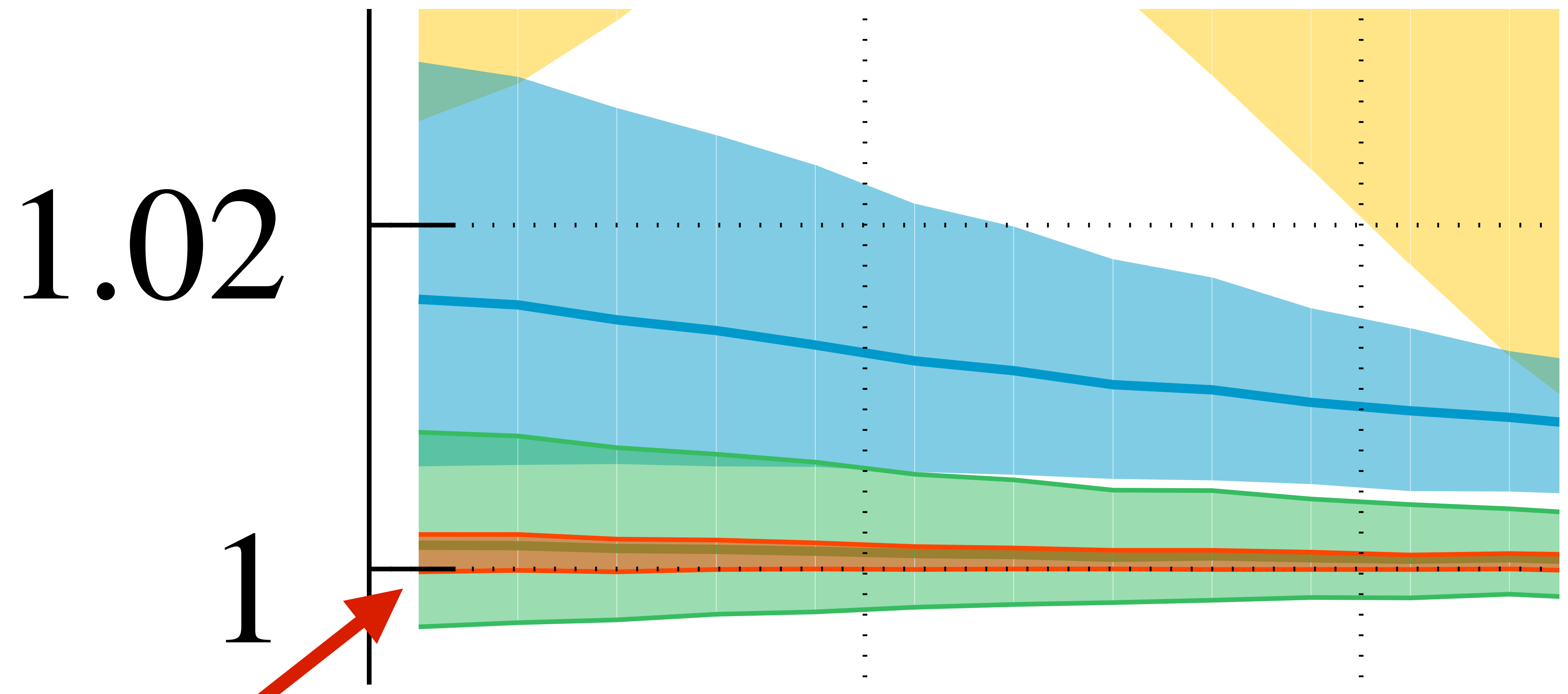
N3LO VBF (no cuts)

VECTOR-BOSON FUSION → HIGGS

- double DIS approximation is powerful tool for VBF, using structure functions for the W/Z production (Han, Valencia & Willenbrock 1992, NNLO by Bolzoni et al 1003.4451)



- Now being extended to N3LO, shows scale uncertainties « 1% for observables inclusive wrt the jets
- good stability from NNLO to N3LO



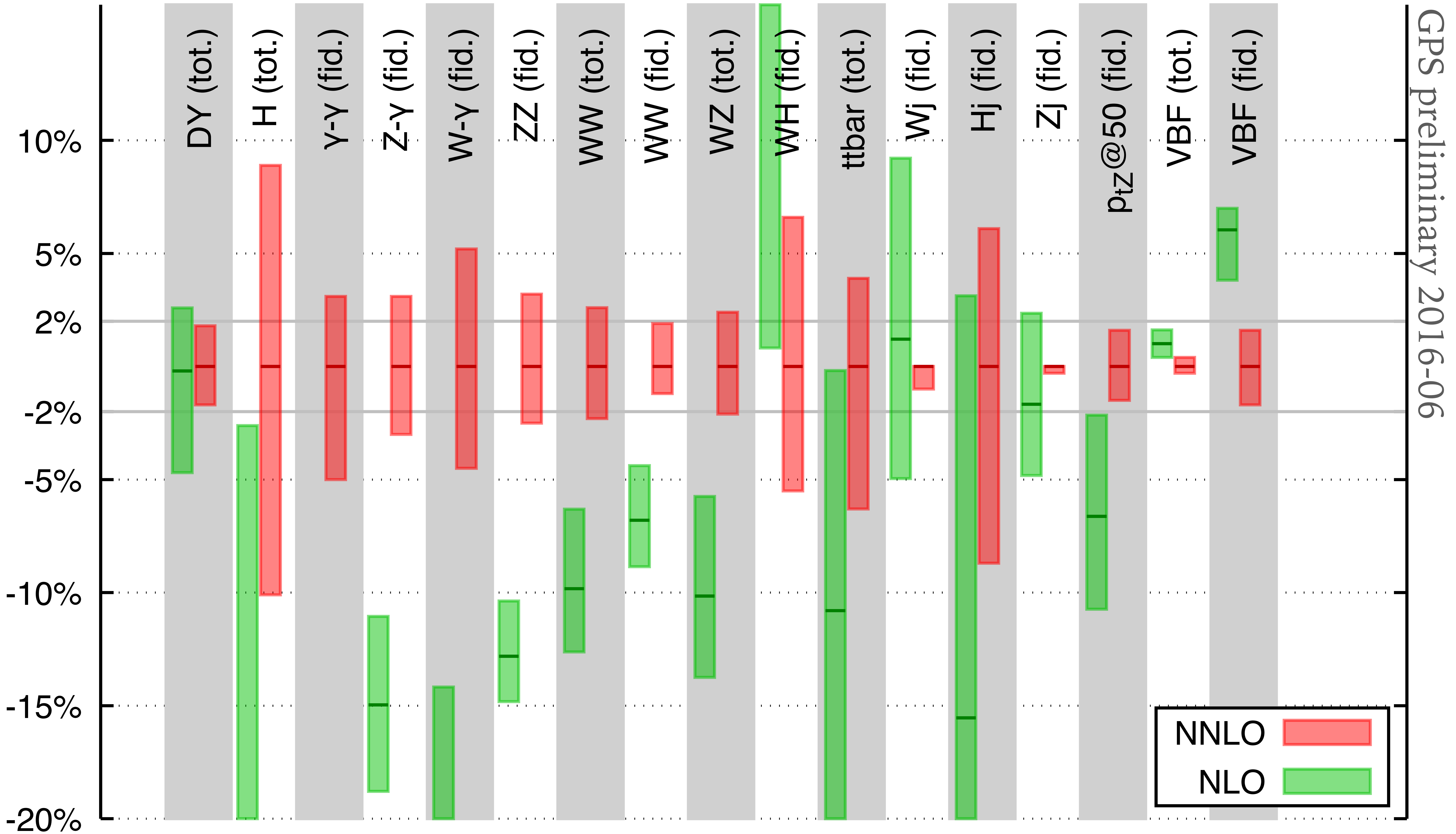
Dreyer & Karlberg, 160x.xxxx

N3LO

Exact in "QCD₁ ⊗ QCD₂"

Non-trivial real-world corrections believed < 1%

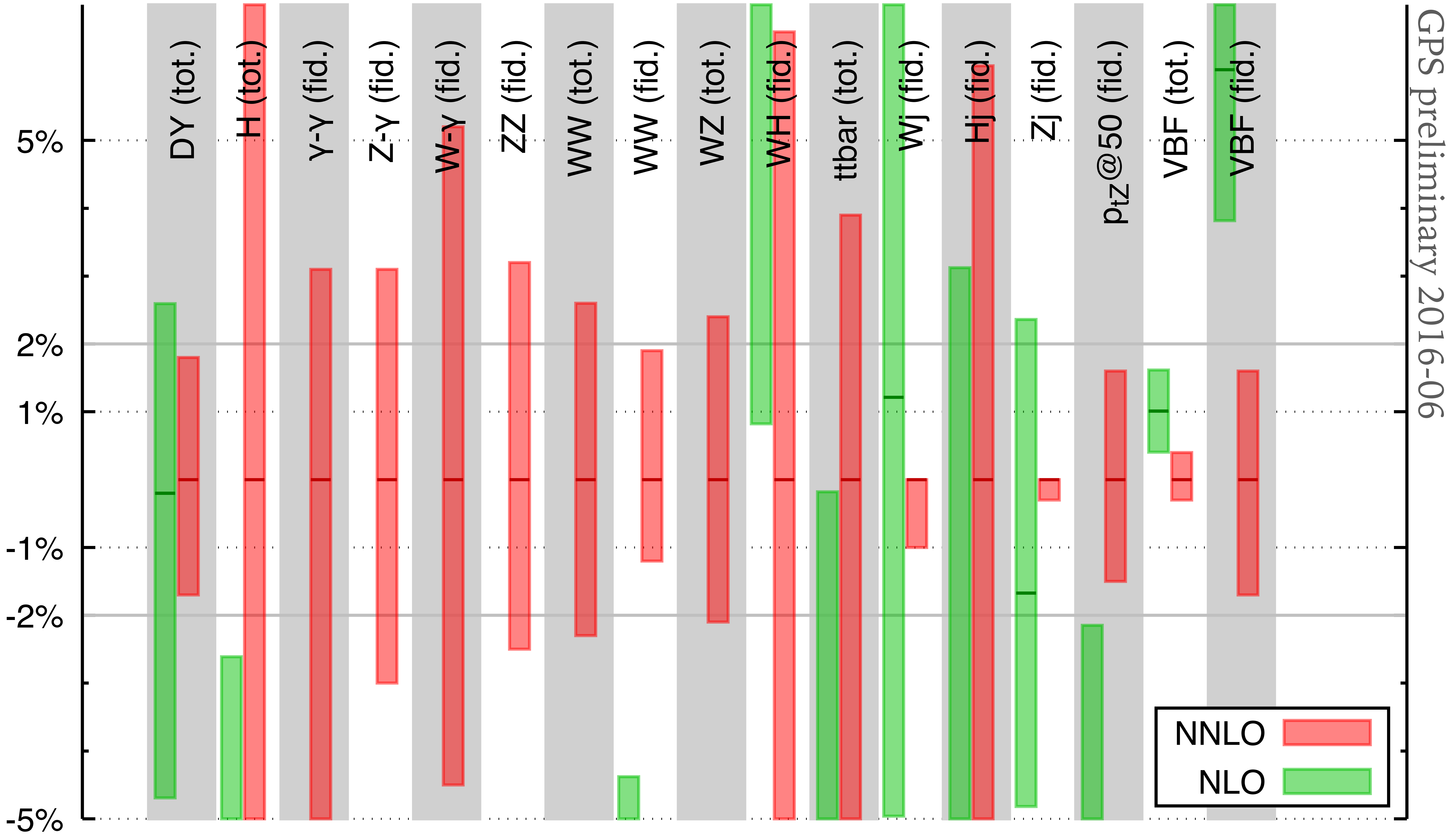
WHAT PRECISION AT NNLO?



For many processes NNLO scale band is ~±2%

Though only in 3/17 cases is NNLO (central) within NLO scale band…

WHAT PRECISION AT NNLO?



For many processes NNLO scale band is ~±2%

Though only in 3/17 cases is NNLO (central) within NLO scale band…

ABSOLUTE CROSS-SECTIONS MEASURED TO ~ 1%?

Beam Imaging and Luminosity Calibration

arXiv:1603.03566v1 [hep-ex]

March 14, 2016

Markus Klute, Catherine Medlock, Jakob Salfeld-Nebgen
Massachusettes Institute of Technology

We discuss a method to reconstruct two-dimensional proton bunch densities using vertex distributions accumulated during LHC beam-beam scans. The x-y correlations in the beam shapes are studied and an alternative luminosity calibration technique is introduced. We demonstrate the method on simulated beam-beam scans and estimate the uncertainty on the luminosity calibration associated to the beam-shape reconstruction to be below 1%.