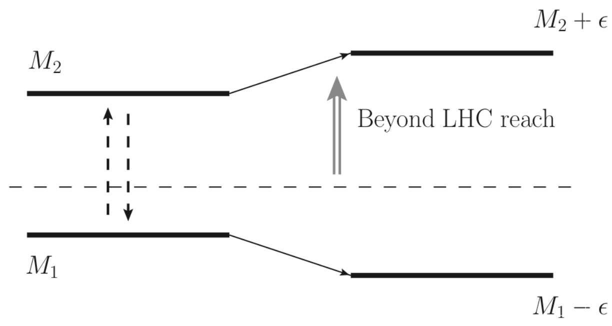
New ideas for a precision measurement of the W boson mass at the LHC

Lorenzo Bianchini

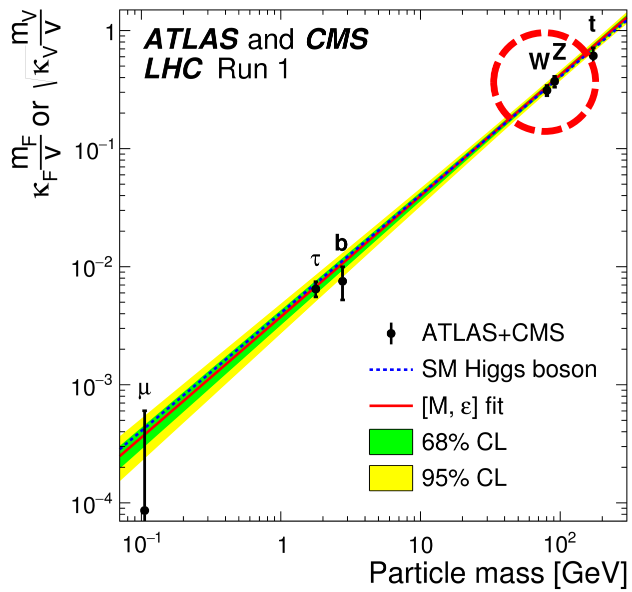
INFN, Sezione di Pisa

Why M_W matters

- W mass is an **Electroweak Precision Observable**
  - Stress-test of the SM → <u>indirect</u> search of NP



- Why is M_W remarkable?
  - **Phenomenology**
    - High sensitivity and robustness of SM prediction.
  - **Opportunity**
    - Theory more precise than experiment.
  - **Case**
    - Slight tension with SM prediction.



What we can learn from M_W

- SM at tree-level → M_W is a function of 3 parameters: G_μ, M_Z, $\alpha_{EM}(M_Z)$

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi\, \alpha_{EM}(M_Z)}{\sqrt{2} G_F (1 - \Delta r)},$$

  - M_h and m_T enter via **radiative corrections**: $\Delta r \approx 3.6\%$ [→ +500 MeV on M_W]

- This relation entails *custodial symmetry* (and the breaking of it):

$$\Delta r = -\frac{3 G_F m_t^2}{8\sqrt{2}\pi^2} \frac{\cos^2\theta_W}{\sin^2\theta_W} + \frac{11 G_F M_W^2}{24\sqrt{2}\pi^2} \log \frac{M_h^2}{M_W^2} +$$

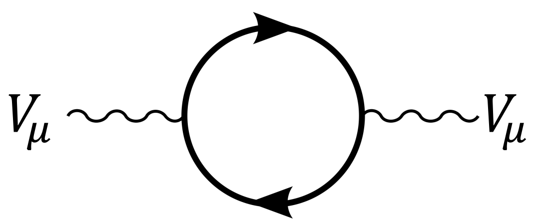
- Higgs multiples with $T > \frac{1}{2}$
- Non-degenerate doublets
- Degenerate chiral fermions
- U(1)'
- ...

SM

BSM ?

M_W as a probe of NP

- Pivotal role in the determination of **oblique parameters** *S,T,U*



$$M_Z^2 = M_{Z0}^2 \frac{1 - \widehat{\alpha}(M_Z)T}{1 - G_F M_{Z0}^2 S/2\sqrt{2}\pi} \, ,$$

$$M_W^2 = M_{W0}^2 \frac{1}{1 - G_F M_{W0}^2 (S+U)/2\sqrt{2}\pi} \, ,$$

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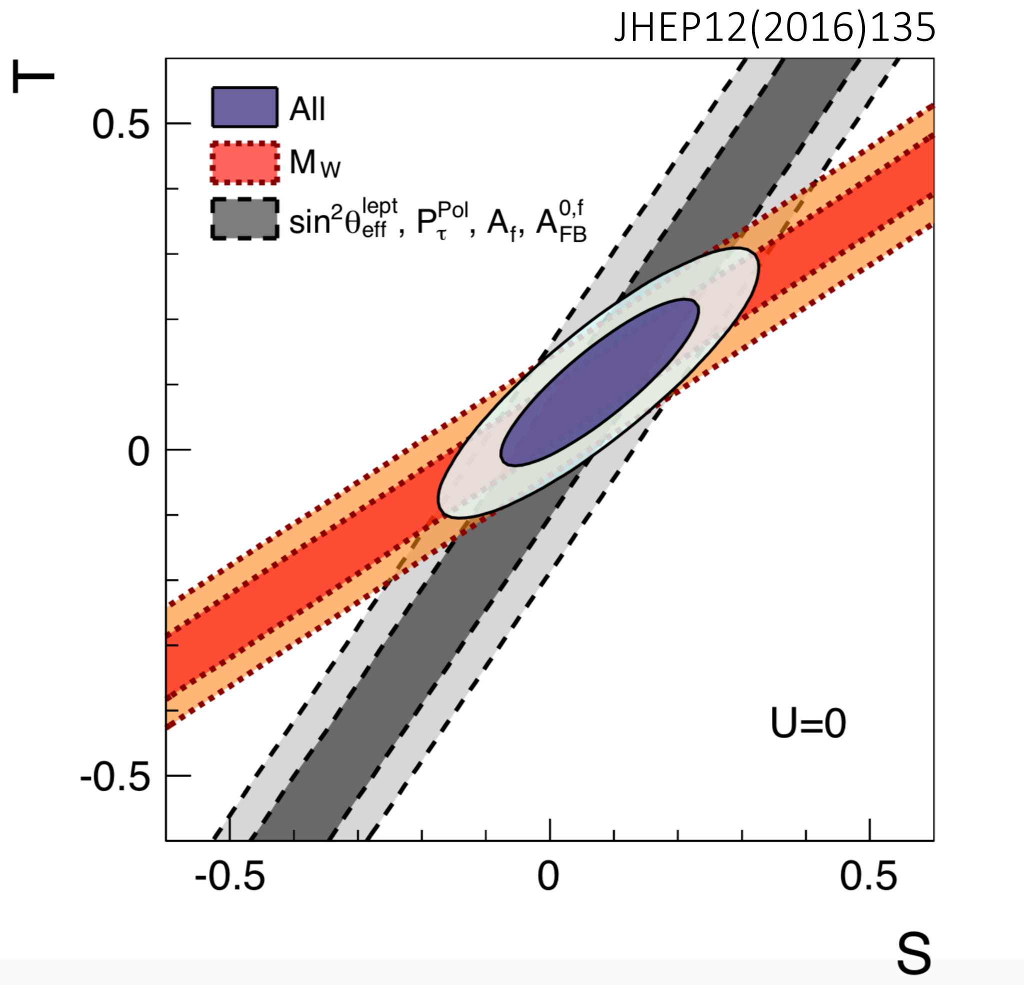
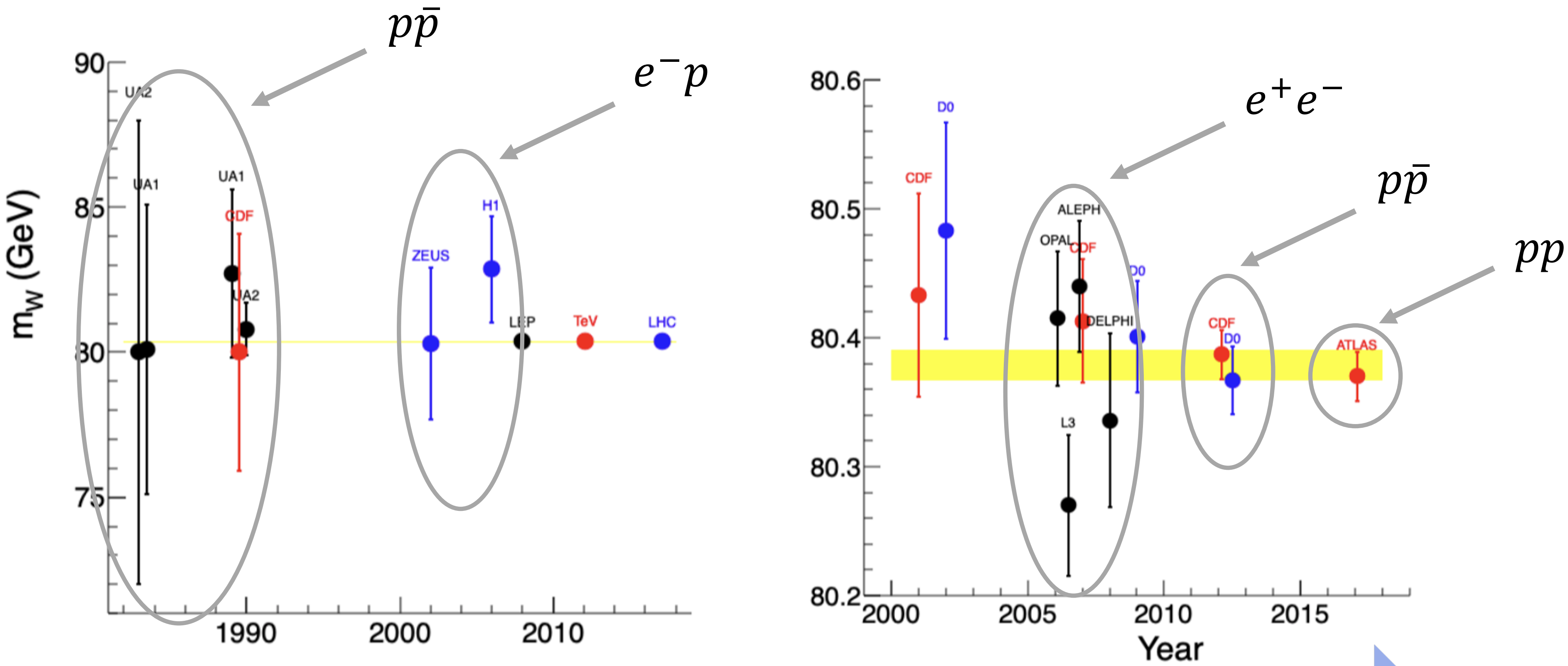


M_W in the history of colliders



5 % *Relative uncertainty* **0.02 %**

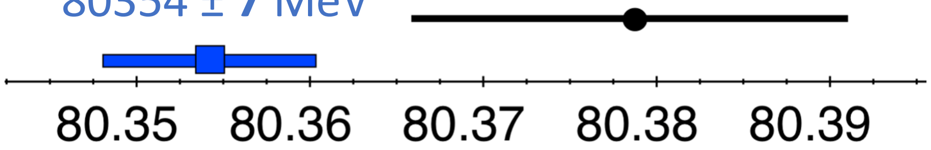
What we know today and what is a useful target

- M.H.O. → 4 MeV
- m_{top} → 4 MeV
- M_Z → 2.6 MeV
- α_s → 2.6 MeV
- $\Delta\alpha^{(5)}_{had}$ → 2.4 MeV

SM:
80354 ± **7** MeV

PDG:
80379 ± **12** MeV

- Tevatron → 15 MeV
- LHC → 19 MeV
- LEP → 33 MeV



- Consistent at $\sim 2\sigma$. *Fluctuation*? *Missing systematic*? *Emerging anomaly*…?

➔ **Target for a <u>new</u> measurement: $\leq$ 10 MeV**

Which future for M_W?

- **Ultimate precision** from next-generation of lepton colliders (>2040)
  - FCC-ee + 2y at threshold → 0.5 MeV
  - Beyond the reach of hadron colliders

- LHC has analyzed just a **tiny fraction** of its data for M_W
  - Strong mandate to probe its limits.

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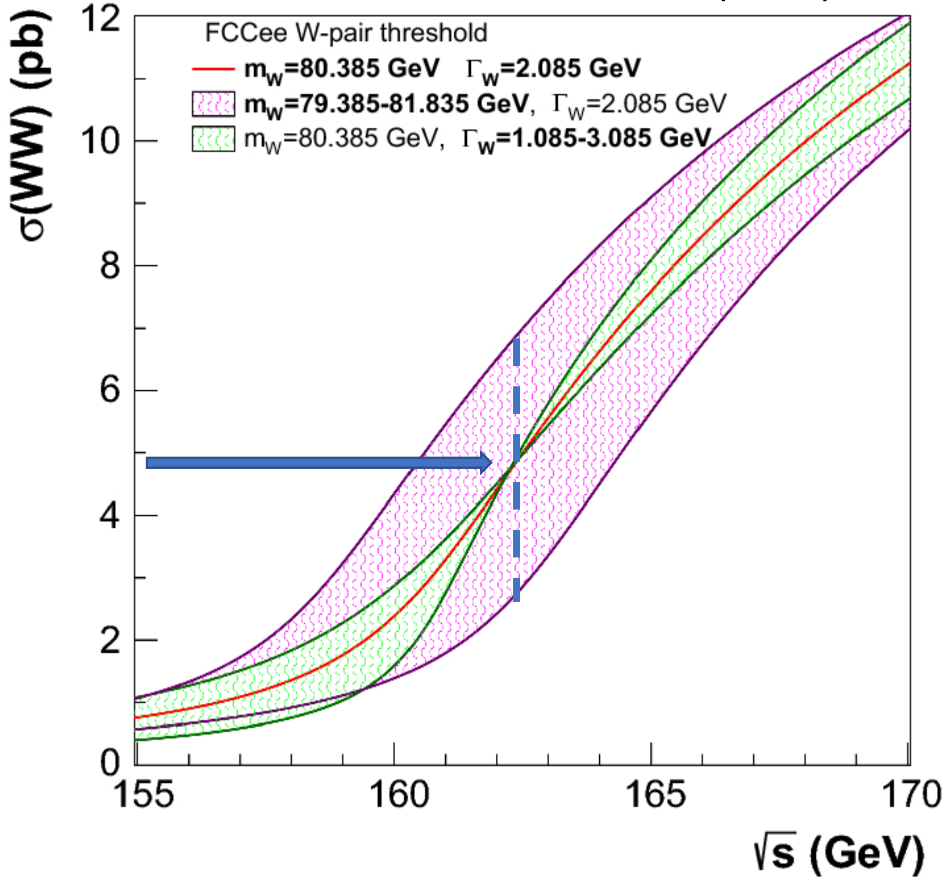
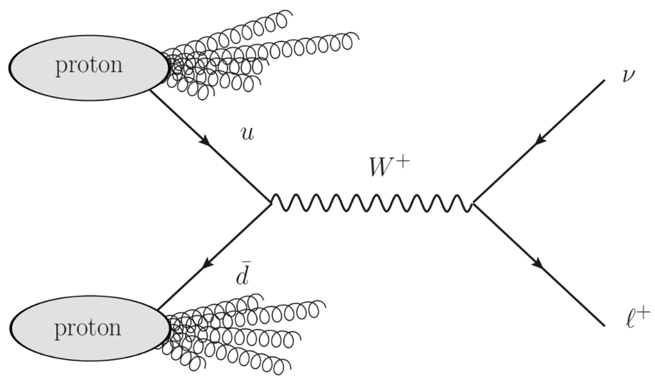
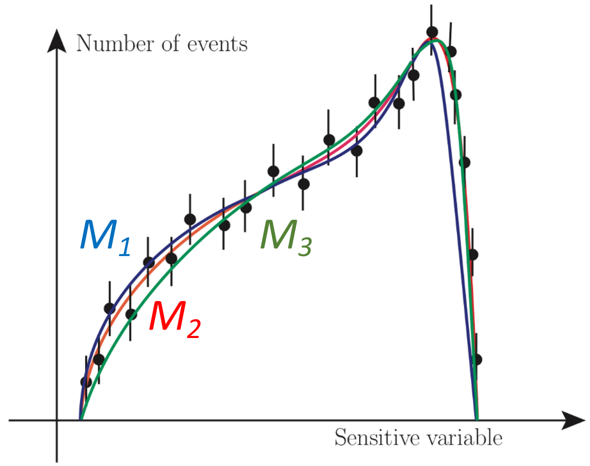


M_W at hadron colliders

- Direct production: $pp \rightarrow W^{\pm} \rightarrow l^{\pm}\nu$
  - Continuous spectrum of *W* momenta
  - Neutrino p_4 unreconstructed

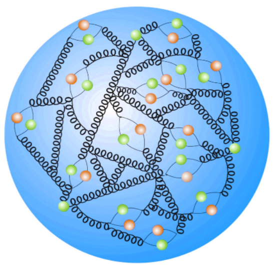


- No "invariant mass" estimator
  - Use of kinematic variables sensitive to M_W (NOT Lorentz-invariant)
- Comparison of experimental distributions to **model-dependent** templates
  - Fit for the "best" M_W



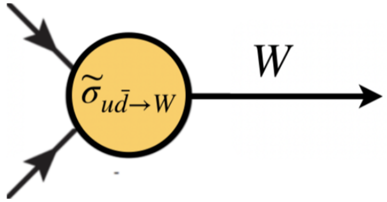
Models of *W* production

Proton **PDFs**



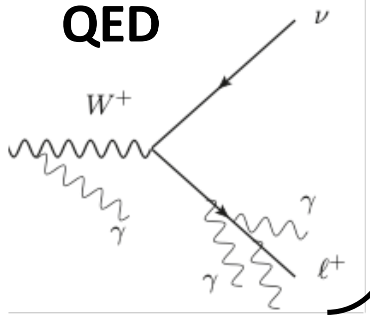
$\otimes$

Perturbative **QCD**



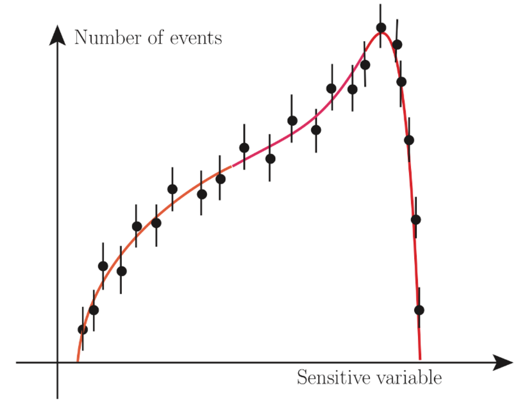
$\times$

Perturbative **QED**

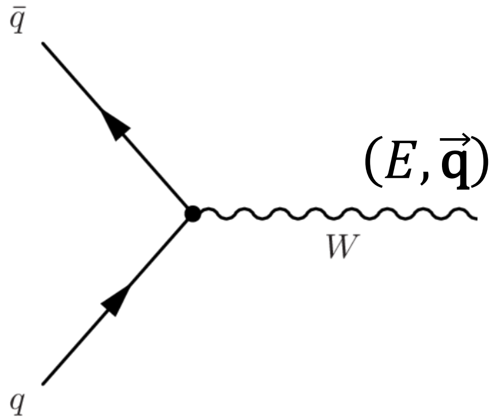


$$\frac{d^6\sigma}{d^3\mathbf{p}_l\, d^3\mathbf{p}_\upsilon}$$

p.d.f. of sensitive variable



Interlude: notation



$$(E,\vec{\mathbf{q}}) = \left(\sqrt{q_T^2+Q^2}\cosh y,\ \boldsymbol{q}_T\,,\ \sqrt{q_T^2+Q^2}\sinh y\right)$$

Virtuality (~ M_W) — Q

Rapidity (~ velocity along beam) — y

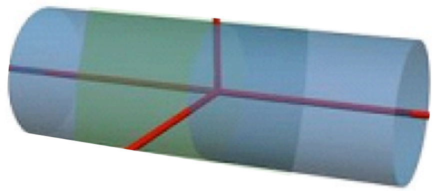
Transverse momentum (to the beam) — $\boldsymbol{q}_T$

W boson dynamics in the lab

- **Longitudinal** dynamics:

$$\frac{d\sigma}{dy} \sim \int dx_1\, dx_2\, \delta\left(x_1 x_2 - \frac{Q^2}{s}\right) \delta\left(y - \ln\frac{x_1}{x_2}\right) \left[u(x_1)\bar{d}(x_2) + \ ...\right]$$

  - "∥" momenta ➔ PDFs



- **Transverse** dynamics:

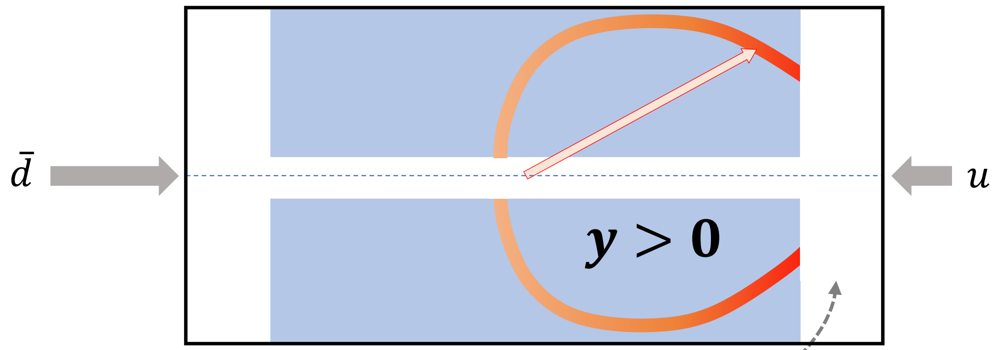
$$\frac{d\sigma}{dq_T^2} \sim \frac{1}{q_T^2}\left[1 + O\left(\frac{q_T}{Q}\right) + O\left(\frac{q_T^2}{Q^2}\right) + \cdots\right]$$

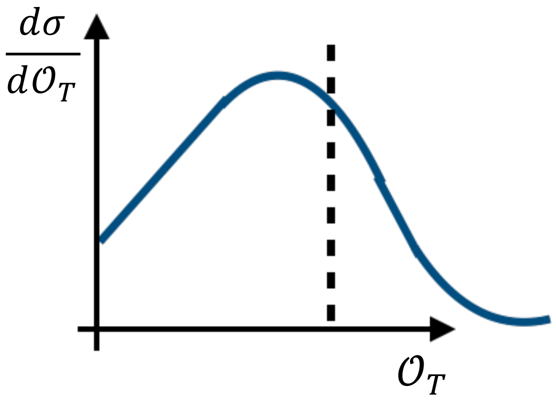
  - "⊥" momenta ➔ *W* decay

➔ **<u>Transverse variables</u>** best suited for studying M_W

The PDF uncertainty

- Why longitudinal dynamics matters?
  - Mostly an **acceptance** artefact





$$\frac{d\sigma}{d\mathcal{O}_T} = \left[\frac{d\sigma}{d\mathcal{O}_T}\right]_{\text{ideal}} \times F(\mathcal{O}_T)$$

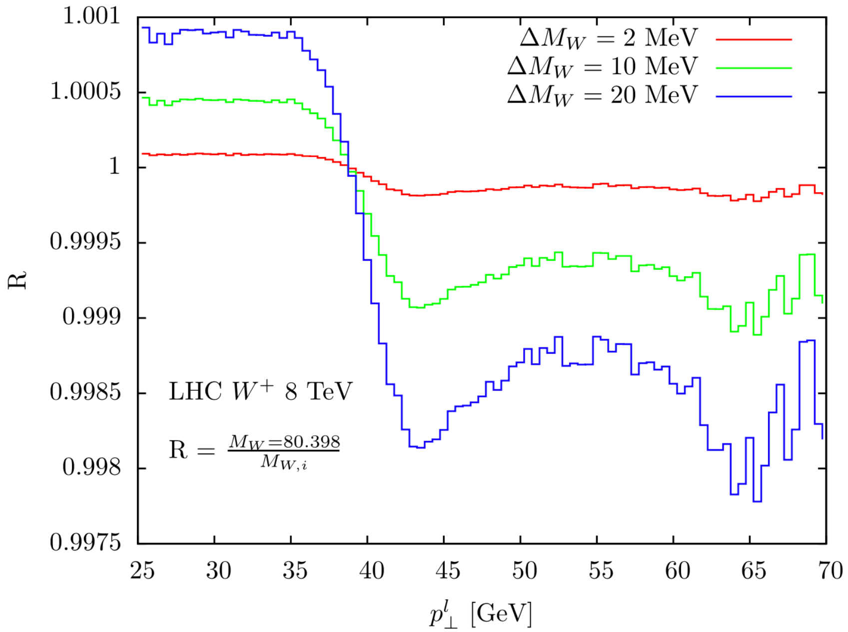
PDF dependence from here!

➔ How large $\frac{\Delta F}{F}$ for a **10 MeV precision** on M_W?

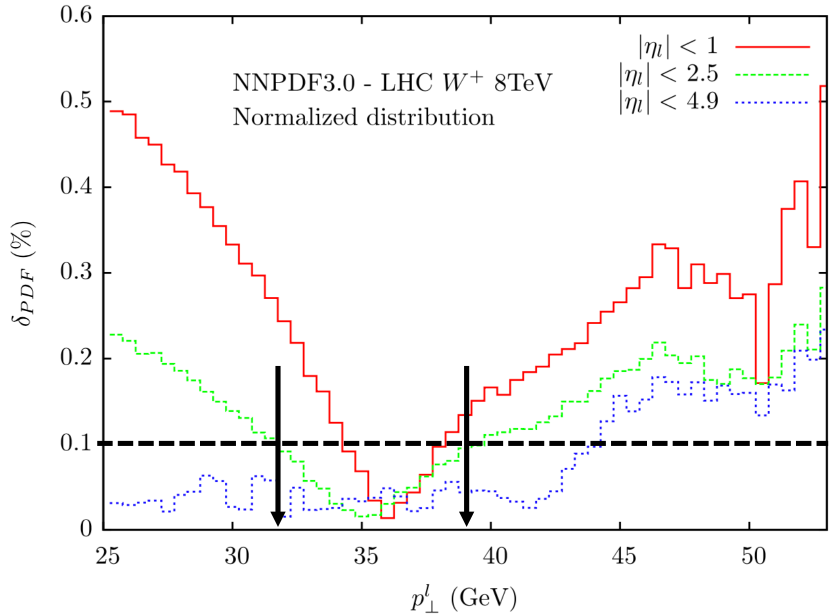
PRD 91 (2015) 113005

Impact of PDF uncertainty on p_T^l spectrum

Impact of 10 MeV shift of M_W



Impact of PDF uncertainty (%)

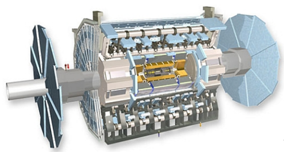


Green curve: **10 MeV → < 0.1%**

➔ At the limit for **standard detectors** ($|\eta| < 2.5$)

PDF mitigation: experimental perspective

- **Joining** experiments:



ATLAS & CMS

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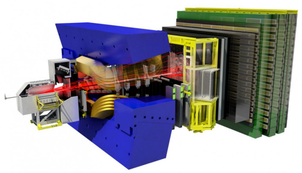
$$\rho = \begin{pmatrix} & \mathbf{G}^+ & \mathbf{G}^- & \mathbf{L}^+ & \mathbf{L}^- \\ \mathbf{G}^+ & 1 & & & \\ \mathbf{G}^- & -0.22 & 1 & & \\ \mathbf{L}^+ & -0.63 & 0.11 & 1 & \\ \mathbf{L}^- & -0.02 & -0.30 & 0.21 & 1 \end{pmatrix}.$$

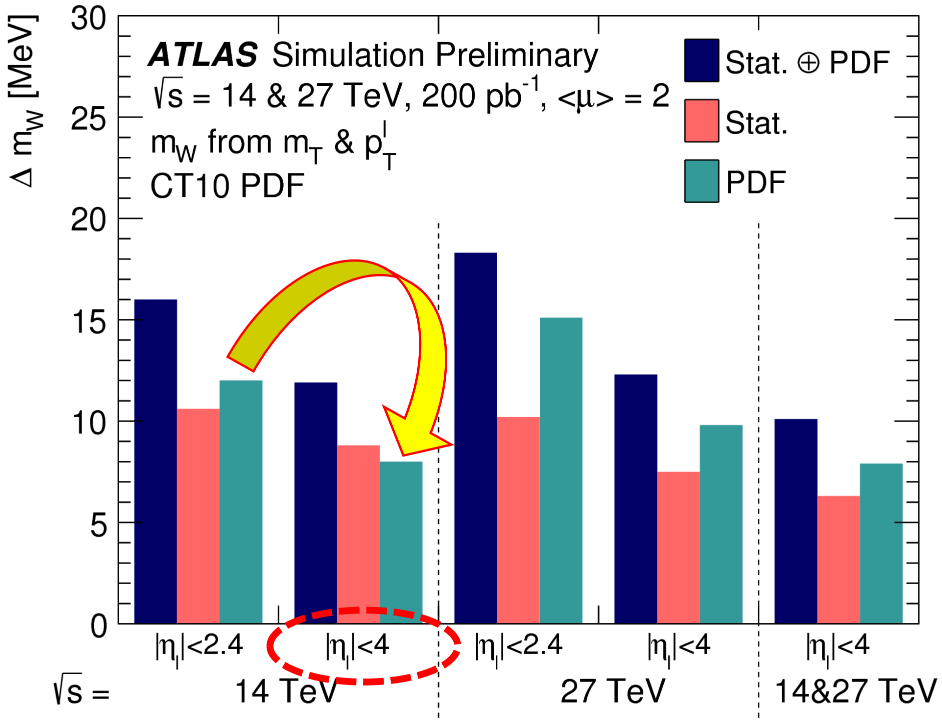
LHCb



➔ 30 ÷ 40% reduction on δ_{PDF}

- Doing ***in situ***:

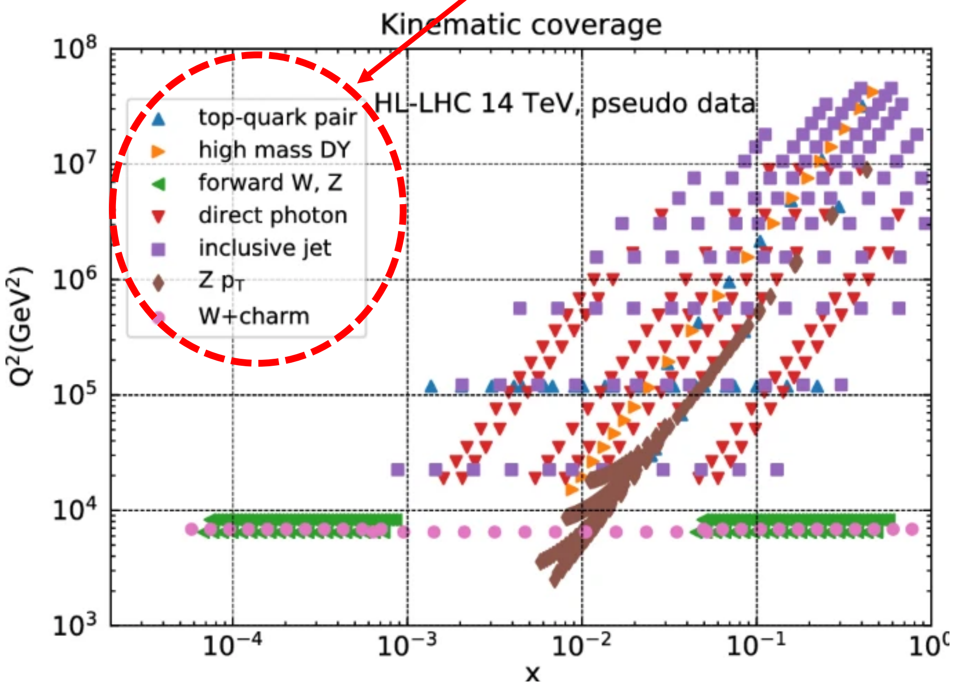
ATL-PHYS-PUB-2018-026

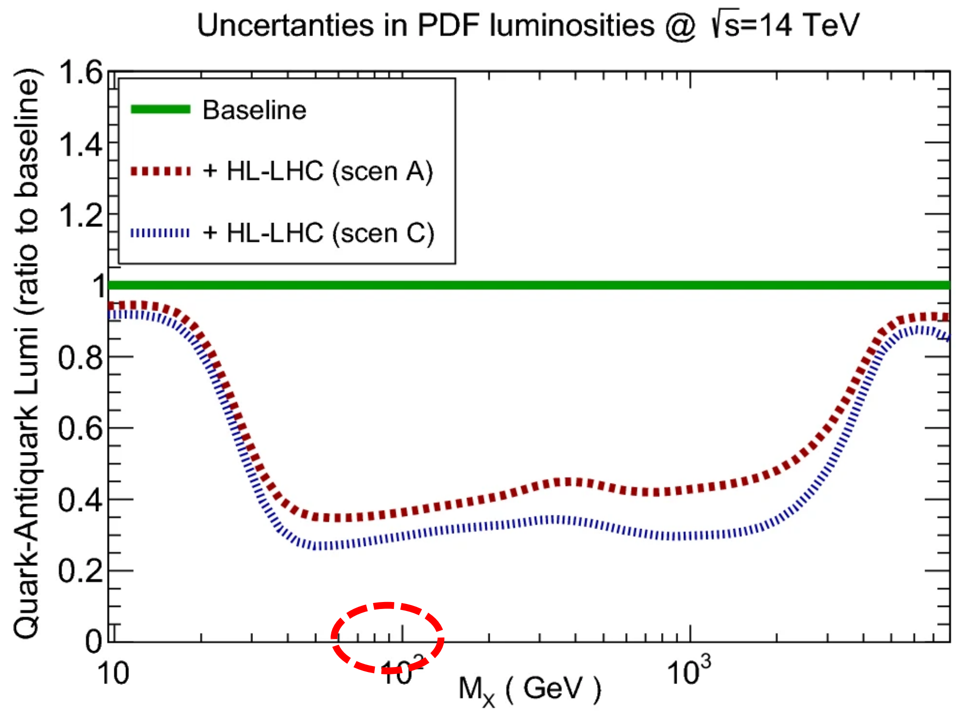


EPJC 78 (2018) 962

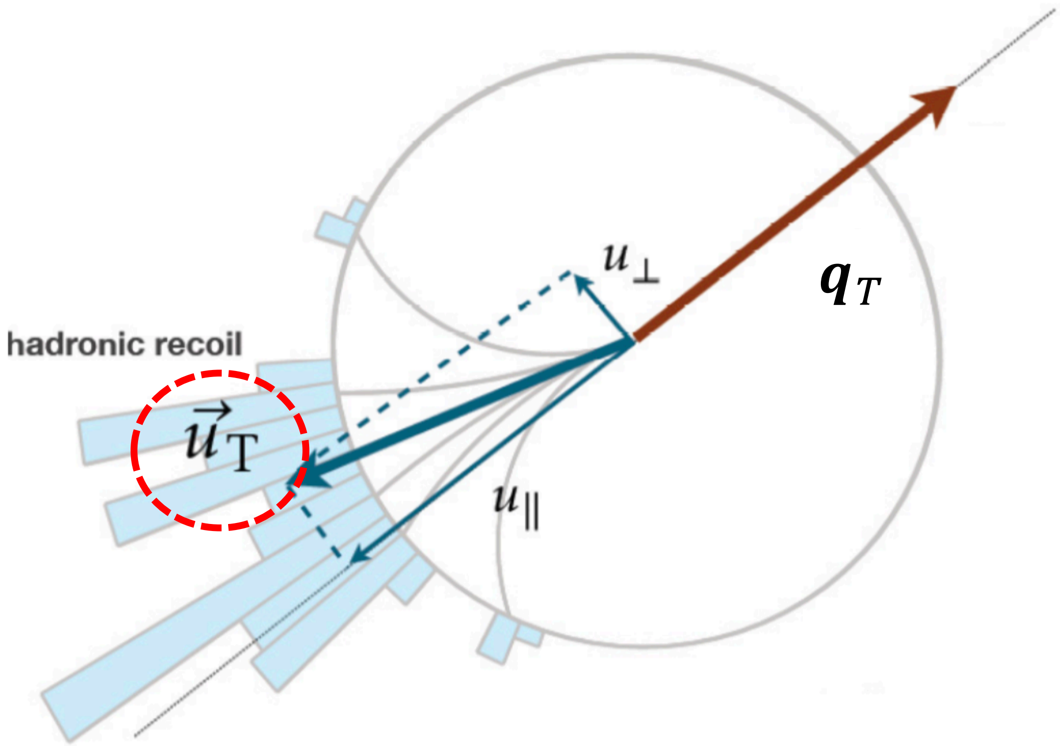
PDF mitigation: experimental perspective

- PDFs will also evolve with **luminosity**
  - Projecting these measurements at HL-LHC ➔ ≈50% reduction on δ_{PDF}





Transverse motion



- Hadronic recoil $\boldsymbol{u}_T$ is a proxy of $\boldsymbol{q}_T$

$$m_T \equiv m(\boldsymbol{p}_T^l, \boldsymbol{p}_T^\nu) = m\left(\boldsymbol{p}_T^l, \boldsymbol{u}_T - \boldsymbol{p}_T^l\right)$$

- $\boldsymbol{u}_T$ resolution degraded by high pile-up (and $\sqrt{s}$) @LHC:

Optimal weights for combining m_T: p_T^l fits at Tevatron and LHC:

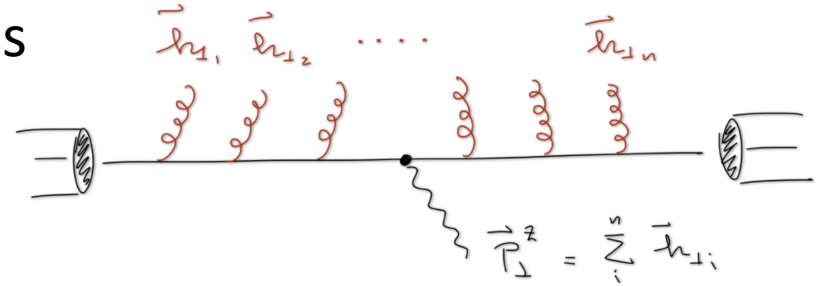
$m_T : p_T^l$	
CDF @ **Tevatron**	ATLAS @ **LHC7**
0.53 : 0.47	**0.14 : 0.86**

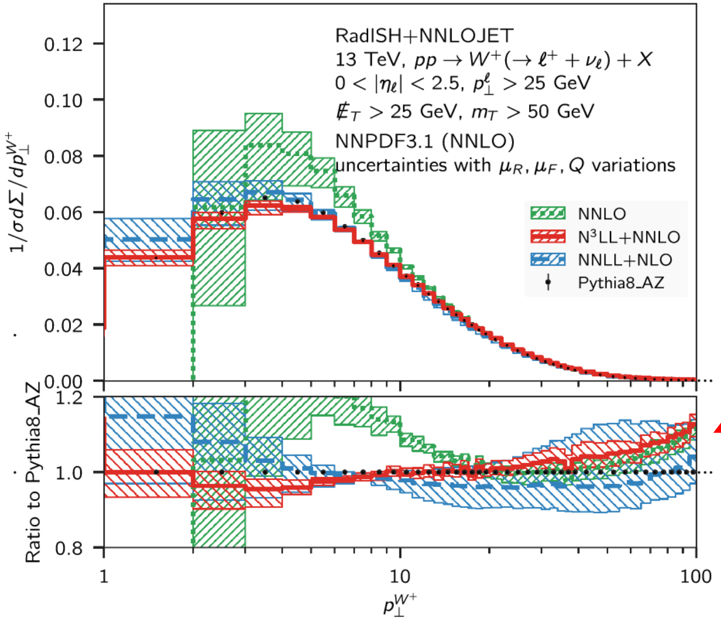
➔ Modeling of q_T is critical at LHC!

Theoretical prediction

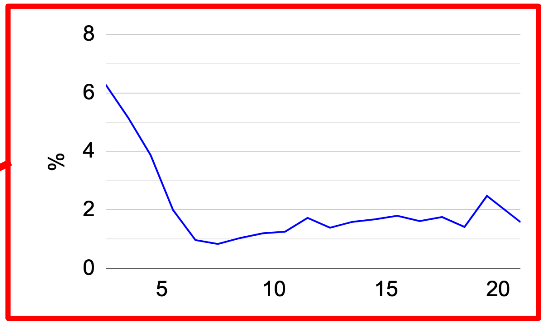
EPJC 79 (2019) 868
and many others…

- All-order resummation of log-divergent series
  - plus, matching to fixed-order at finite q_T
  - State-of-the-art: N^{3}LL + NNLO





Best theoretical precision (%)



➔ Which precision needed for **10 MeV** on M_W?

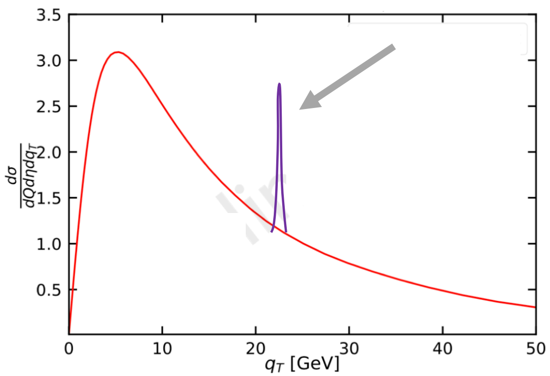
A qualitative assessment

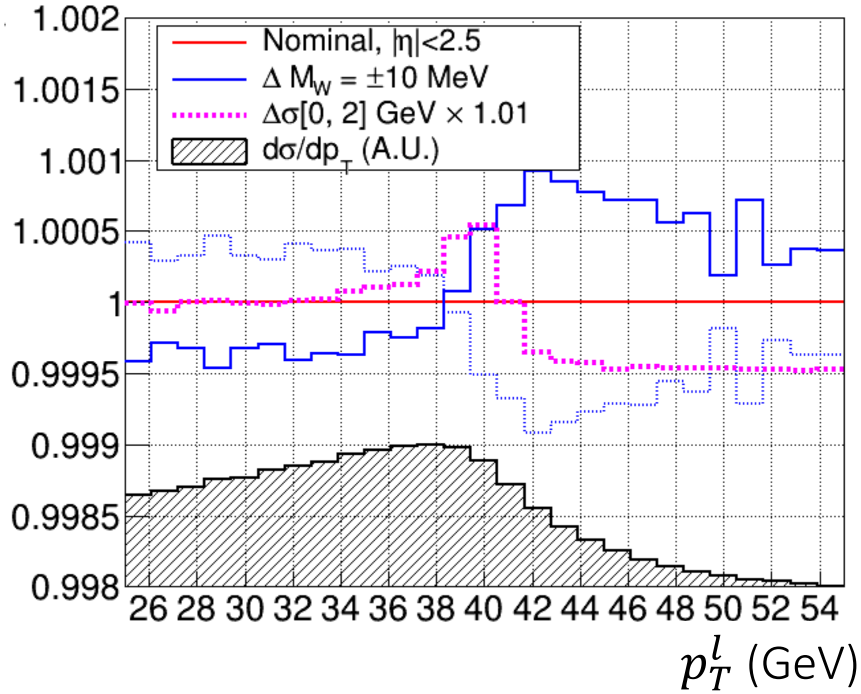
BLUE

10 MeV shift of M_W

MAGENTA

1% perturbation of $\frac{\Delta\sigma}{\Delta q_T}$





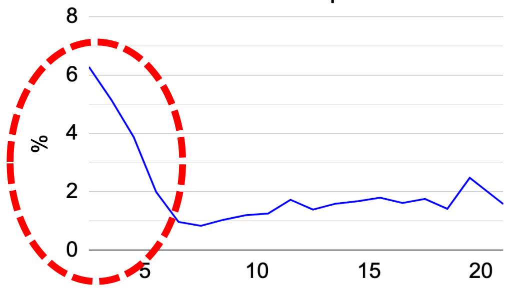
Rule-of-thumb:

2% for $q_T \lesssim 5$ GeV

➔ $\boldsymbol{\mathcal{O}(10)}$ **MeV** on M_W

REMINDER

Best theoretical precision (%)



Enhancements to q_T model: theory

- $W^{\pm}/Z$ ratio
  - Common uncertainties **cancel in the ratio**
  - q_T of Z boson measured to < 1% precision

JHEP 12 (2019) 061

- Correlation scheme matters
  - One choice *vs* another → ~ tens of MeV on M_W
  - Reliable and agreed prescription still **missing**.

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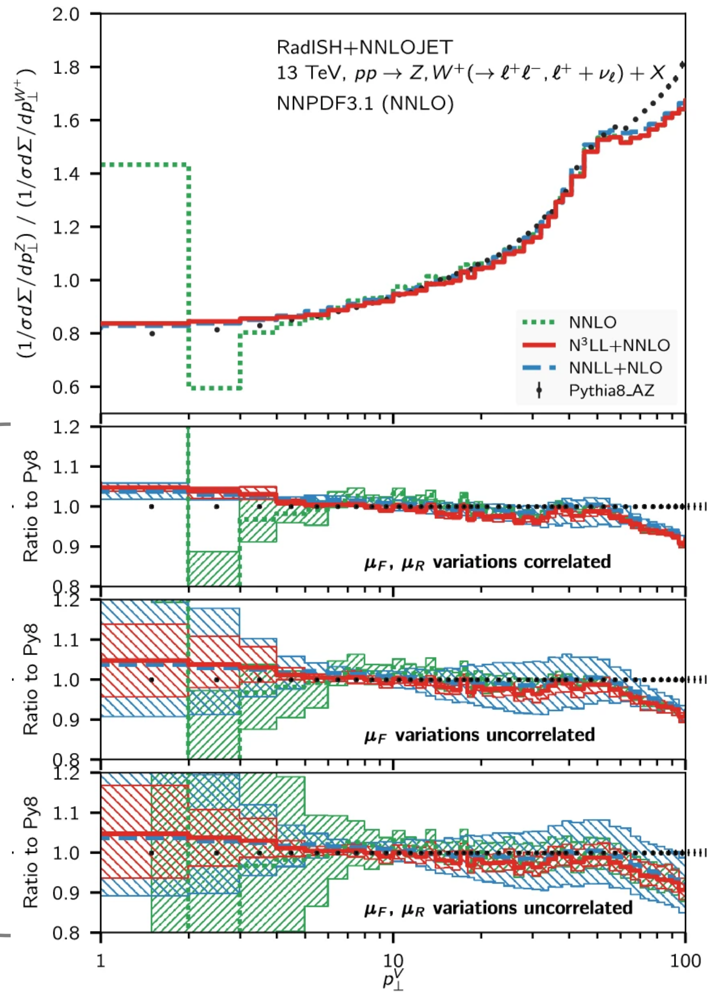
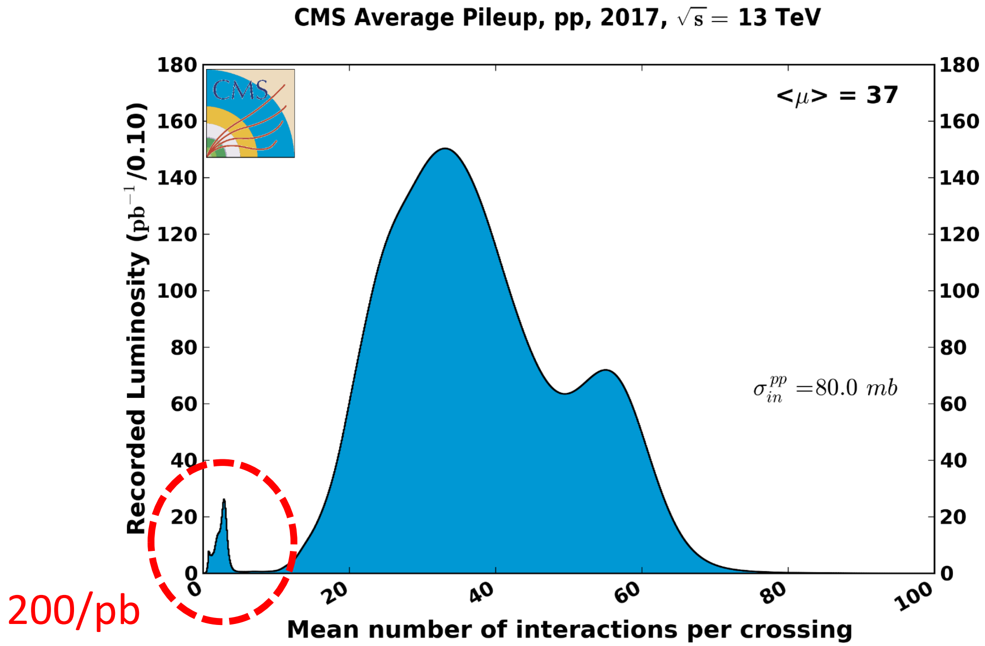


Enhancements to q_T model: experiment

- Precision measurement of $W\ q_T$
  - Special LHC runs can improve $\sigma(u_T)$
- Focus on <u>critical</u> region $q_T \lesssim 5$ GeV
  - **Challenging** detector resolution even at low PU



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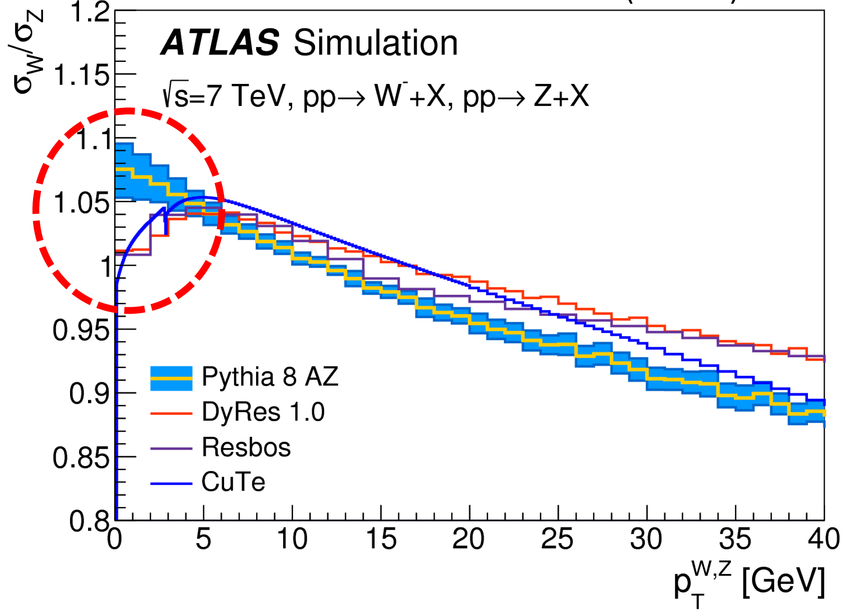

Wrapping up on model uncertainties

- ATLAS measurement @ 7 TeV ➔ predominance of **model uncertainties**
  - PDF, QCD contribute by $\simeq$ 8, 9 MeV.

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Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

➔ Some **breakthrough** needed to reach the **<u>10 MeV target</u>**!

The breakthrough: data!

- LHC → <u>high-luminosity</u> discovery machine
  - unprecedented **statistical power** for producing EWK bosons

	LEP	Tevatron	LHC
# of *W* bosons	**80,000**	**3,000,000**	**1,000,000,000**

× 300

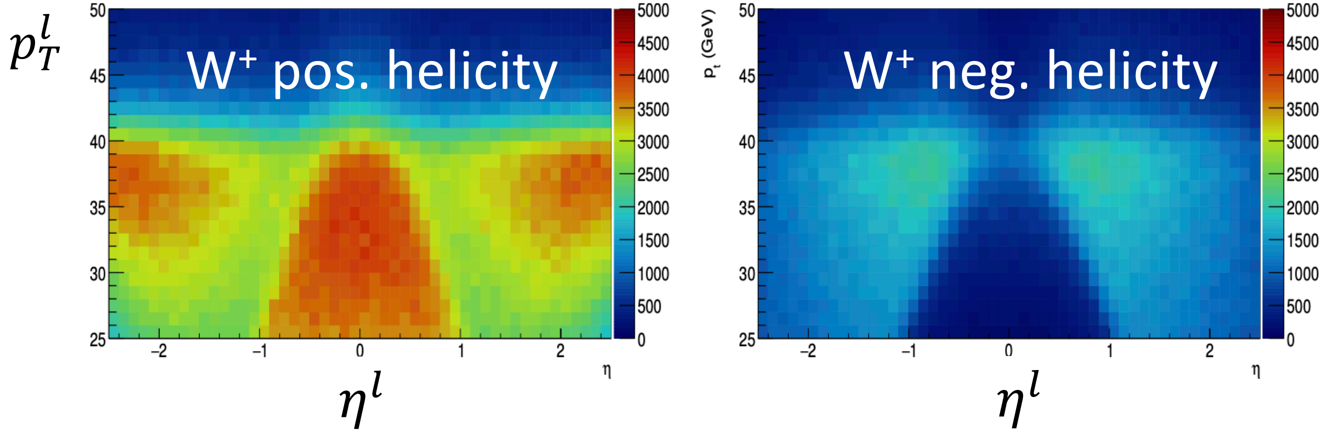
× 30,000

How to make the best of it?

Ideas for an ancillary measurement

- Measurement of the **rapidity spectrum** for the two **helicity states** of $W^{\pm}$

JHEP12(2017)130



See also:
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  - Observation: 2D spectrum (p_T^l, η^l) provides simultaneous information on rapidity and helicity of the $W^{\pm}$.

- y e h depend on quark flavor and momentum→ constraint *in situ* of PDFs
  - Corroborated by recent CMS work [PRD 102 (2020) 092012]

Towards an agnostic model

- Precision measurement of differential spectrum ➔ model constraint
  - Can one push this **paradigm** to its limit?
- <u>First principles</u>: generic cross-section for *pp* → *V* → *l* ν :

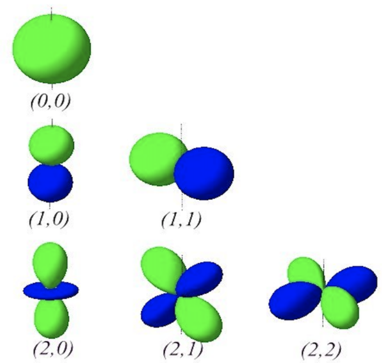
[1] $$\frac{d\sigma}{d^4q\; d\cos\vartheta\; d\varphi} = \frac{3}{16\pi}\sum_{i=-1}^{7}\frac{d\sigma_i}{d^4q}\, g_i(\theta,\varphi)$$

$$= \frac{3}{16\pi}\frac{d\sigma_{-1}}{d^4q}\left(1+\cos^2\theta + \sum_{i=0}^{7} A_i(q_T,|y|)\, g_i(\theta,\varphi)\right)$$

Unpolarized cross-section

Angular coefficients

$$\begin{aligned}
g_{-1}(\theta,\varphi) &= 1+\cos^2\theta\,,\\
g_0(\theta,\varphi) &= 1-\cos^2\theta\,,\\
g_1(\theta,\varphi) &= \sin(2\theta)\cos\varphi\,,\\
g_2(\theta,\varphi) &= \tfrac{1}{2}\sin^2\theta\cos(2\varphi)\,,\\
g_3(\theta,\varphi) &= \sin\theta\cos\varphi\,,\\
g_4(\theta,\varphi) &= \cos\theta\,,\\
g_5(\theta,\varphi) &= \sin^2\theta\sin(2\varphi)\,,\\
g_6(\theta,\varphi) &= \sin(2\theta)\sin\varphi\,,\\
g_7(\theta,\varphi) &= \sin\theta\sin\varphi\,.
\end{aligned}$$



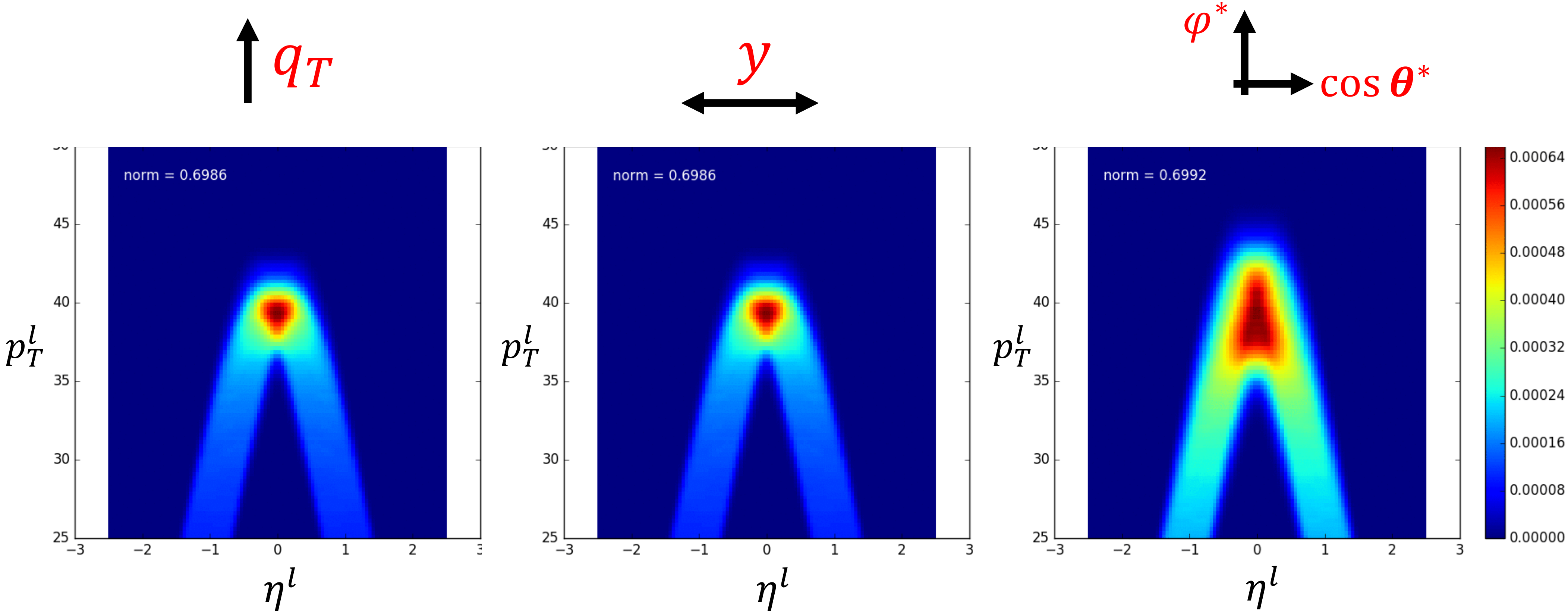
Towards an agnostic model

- Eq. [1] → joint p.d.f. (p_T^l, η^l) as a linear combination of a **finite** and **complete** set of templates:

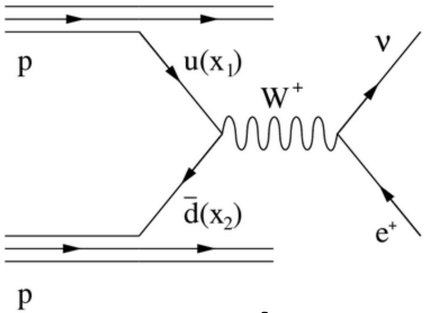
$$\frac{\Delta^2\sigma}{\Delta p_T^l\ \Delta\eta^l} = \sum_{\Delta q_T, \Delta|y|} \frac{\Delta^2 \boldsymbol{\sigma_{-1}}}{\Delta \boldsymbol{q_T}\ \Delta|\boldsymbol{y}|}\left(T_{-1}(p_T, \eta \mid \boldsymbol{M_W}) + \sum_{i=0\ldots4} \boldsymbol{A_{i,\Delta q_T,\Delta|y|}} \times T_i(p_T, \eta \mid \boldsymbol{M_W})\right)$$

  - Normalizations → *W* production & decay dynamics
  - Template shape → M_W

Towards an agnostic model

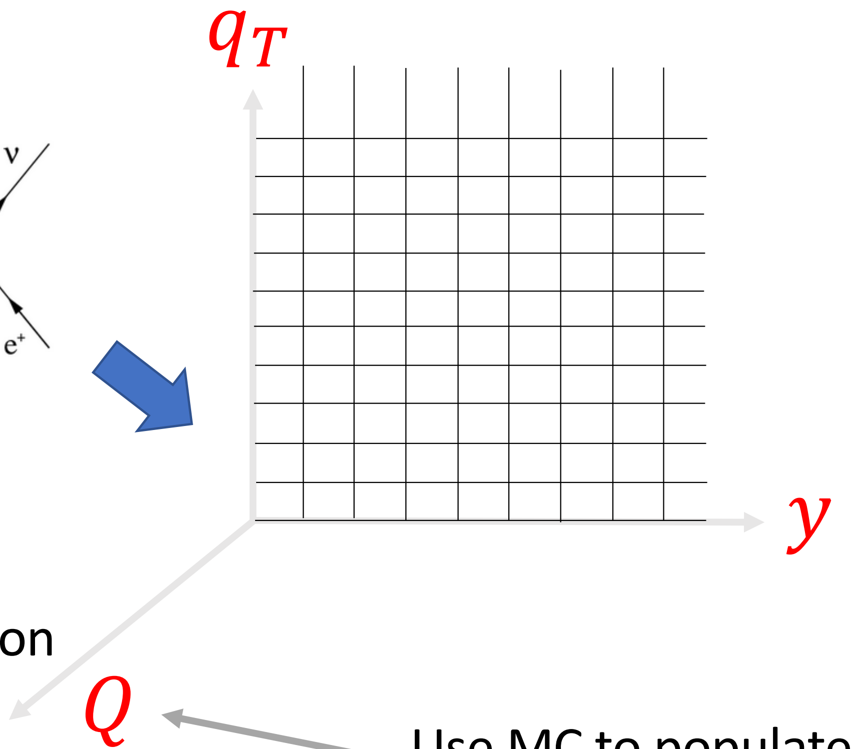


In practice



MC sample

- pp → W± → l±ν
- QED
- Detector simulation



Use MC to populate this dimension

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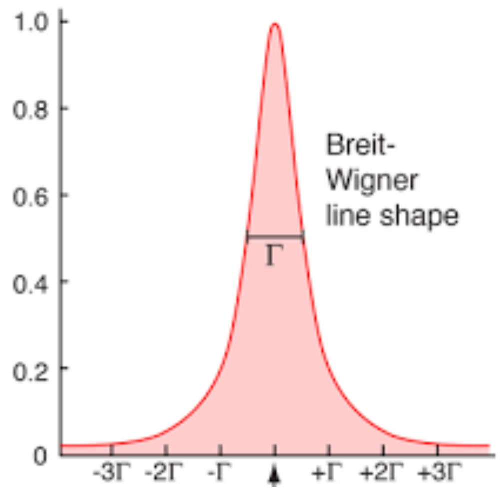
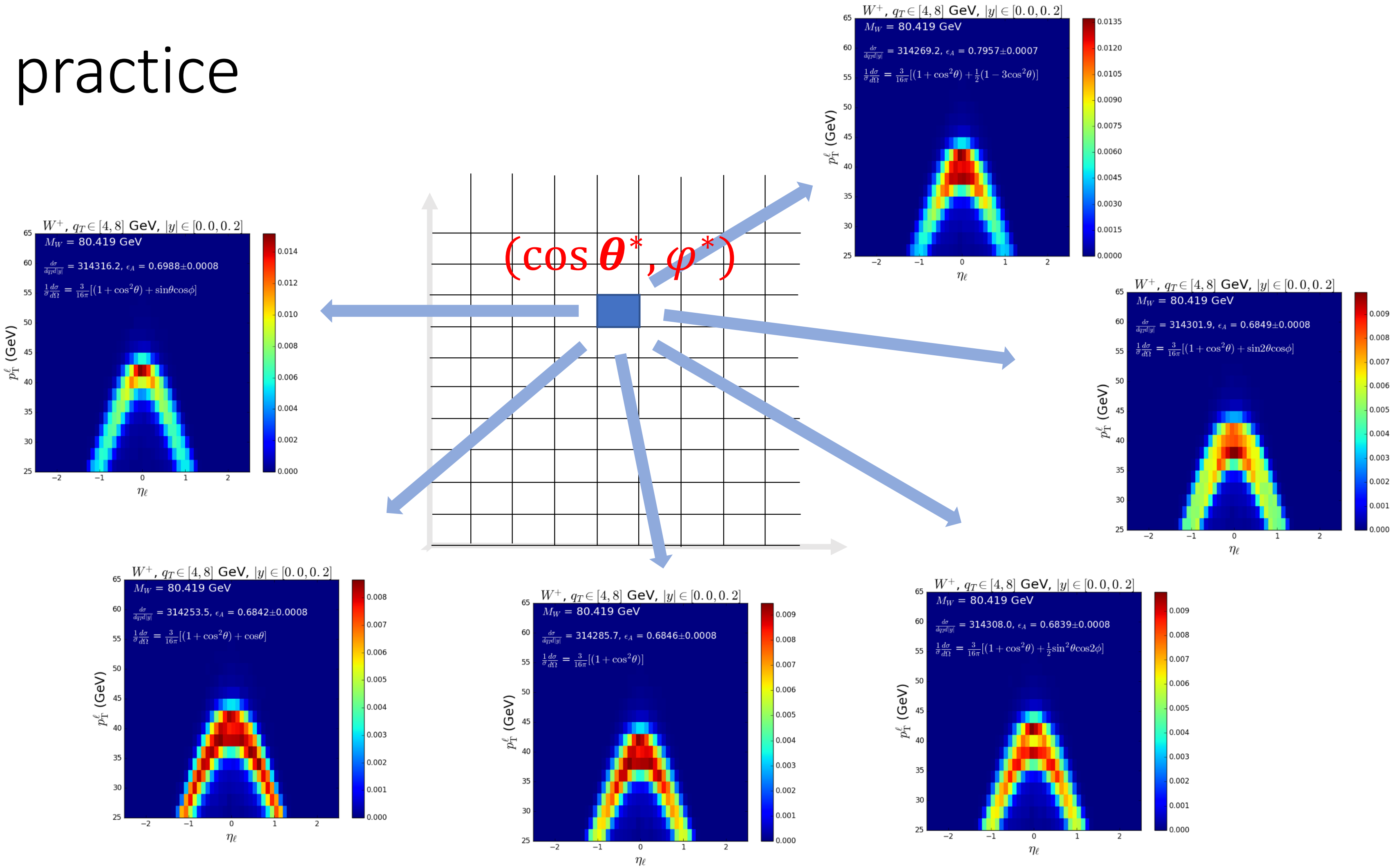
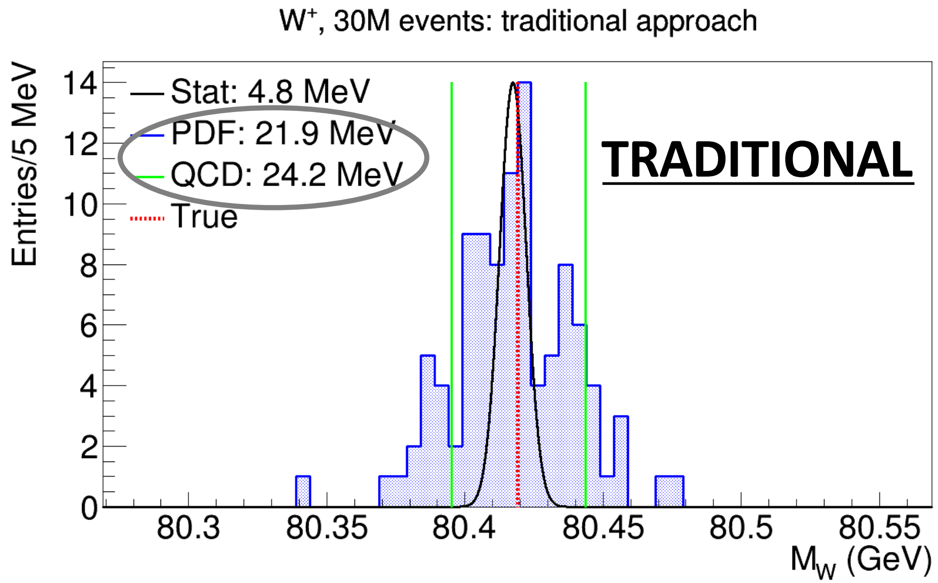


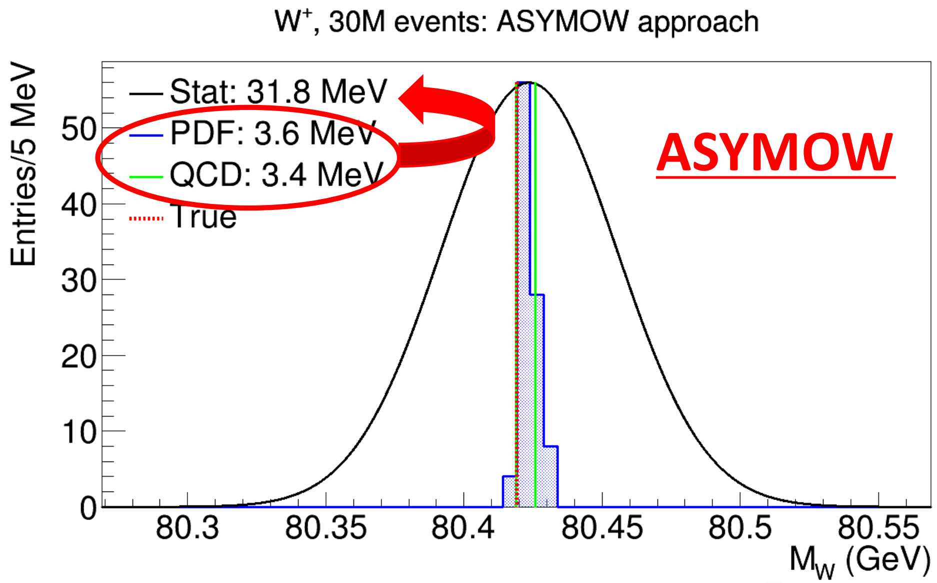
In practice


(cos θ*, φ*)
W+, qT ∈ [4, 8] GeV, |y| ∈ [0.0, 0.2]
MW = 80.419 GeV
= 314269.2, εA = 0.7957±0.0007
= 314316.2, εA = 0.6988±0.0008
= 314301.9, εA = 0.6849±0.0008
= 314253.5, εA = 0.6842±0.0008
= 314285.7, εA = 0.6846±0.0008
= 314308.0, εA = 0.6839±0.0008
pT (GeV)
ηℓ

Proof of concept

- Which **statistical precision** on M_W?
  - Studied on MC simulation (~1300 templates, ~300 free parameters)





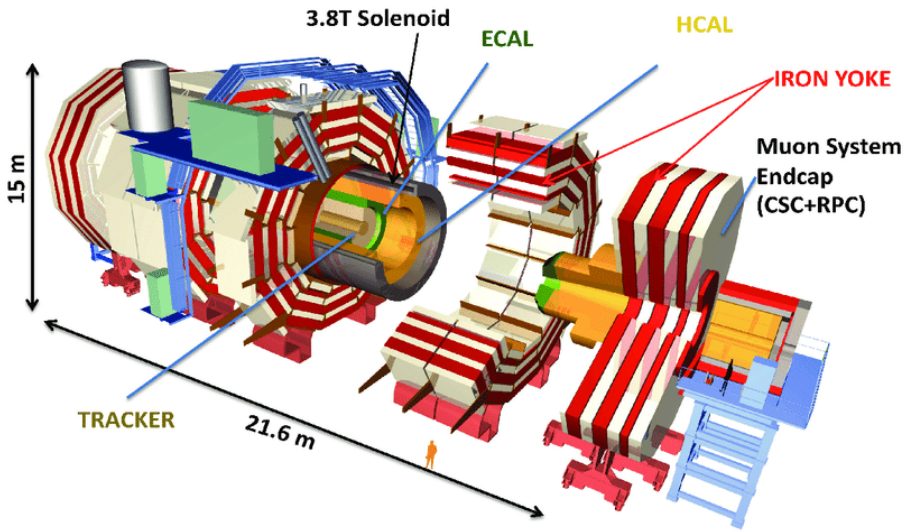
Model uncertainties → systematic bias **> 10 MeV**

Model uncertainties → **statistical** uncertainty

Experimental challenges

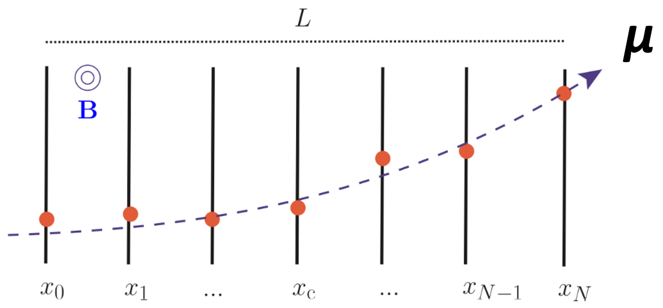
- ΔM_W(stat.) = 4 MeV → $L_{int} \simeq 300$/fb.
  - Possible with Run2 + Run3
  - $\mathcal{O}(100)$ more events than any M_W measurement to date
- Challenge: keep **experimental systematics** under control
  - Background subtraction
  - Detector calibration
  - Residual theory uncertainty
- Experiment → CMS
  - Superior performance Tracker + μ-system:

  → Priority to **measurement with muons**

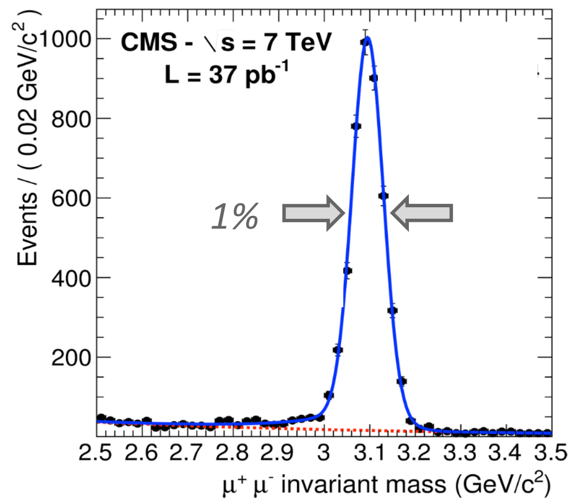


Example: momentum scale calibration

- **Target**: $\Delta p/p < 10^{-4}$
  - ~300 nm biases on mean track curvature;
  - unique use-case for such a precision!



- Intense B-field + silicon tracker
  - J/Ψ as standard candle → closure on the Z
  - ~$2{\times}10^{-4}$ achieved at 7 TeV [CMS-PAS-SMP-14-007]



- An historical & ongoing effort driven by CMS group @ SNS

Expected performances

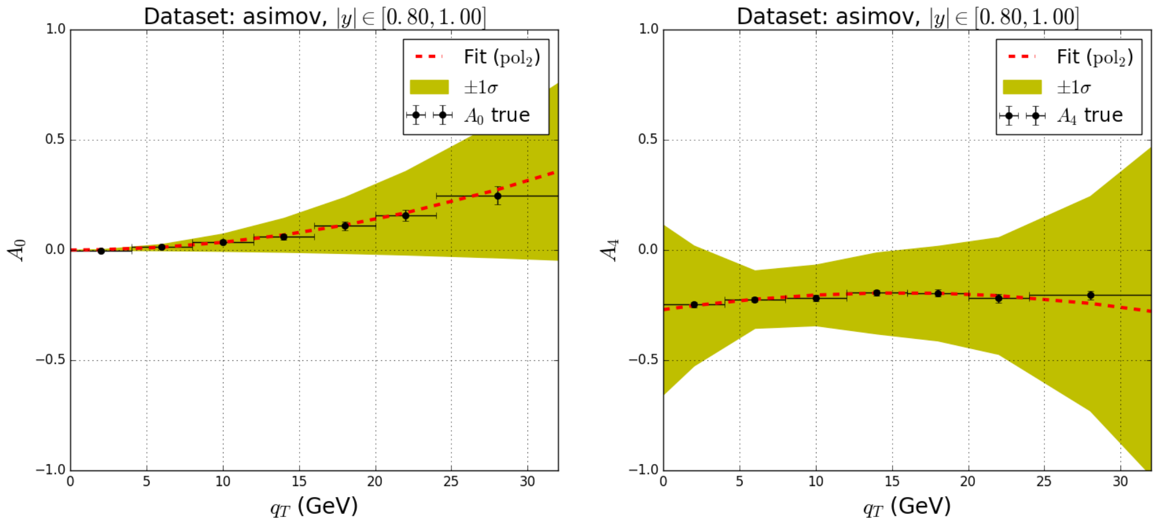
- Three scenarios of increasing experimental success:
  - $\Delta M_W \simeq$ **10 MeV** appears to be a robust deliverable
  - ➔ Possible by overcoming the model-dependence bottleneck

		Stat.	Exp.	Bkg.	QCD	EW	PDF	**Tot.**
Reference (ATLAS @7 TeV)		7	6	5	8	6	9	**19**
ASYMOW	Conservative	4	8	5	3	3	3	**11**
	Intermediate	4	4 / 8	5 / 3	3	3	3	**9 / 10**
	Aggressive	4	4	3	3	3	3	**8**

~2 better than **single-experiment** to date

Not just M_W

- Multi-differential model is a "nuisance"… but also a by-product
  - Tighter **PDF** constraints
  - Benchmark for **precision calculations**
    - e.g., a recoil-free measurement of q_T



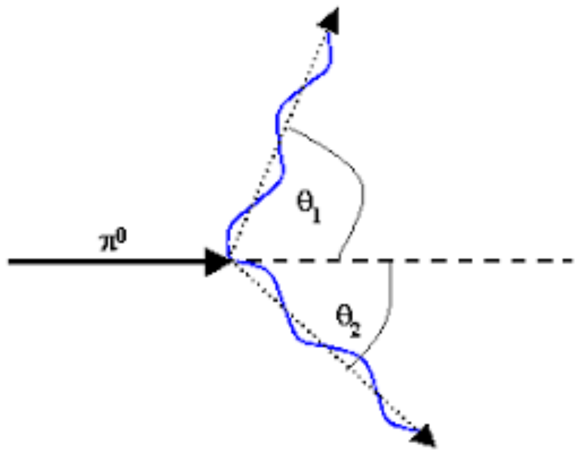
Examples of **angular coefficients** extracted together with M_W

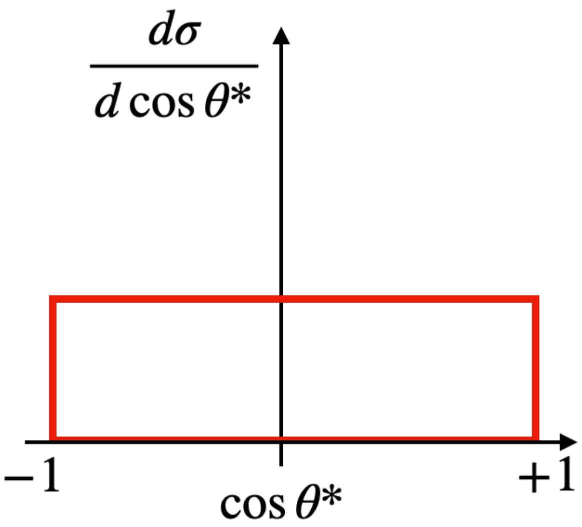
One last idea…

- ASYMOW → profile the full underlying production mechanism while measuring M_W
  - Can it be done with **fewer nuisances**?

A subtle point of invariance

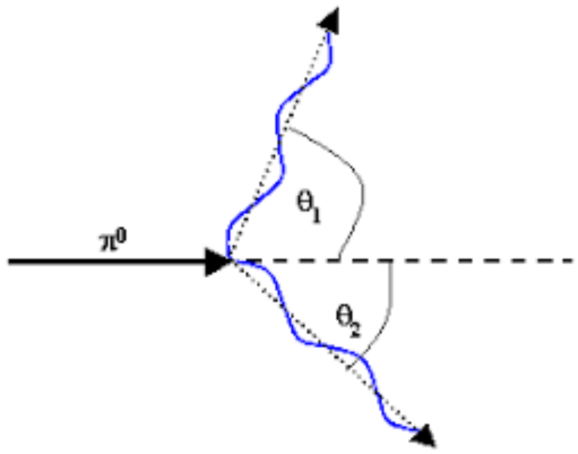
- Remember the famous π^0 decay…

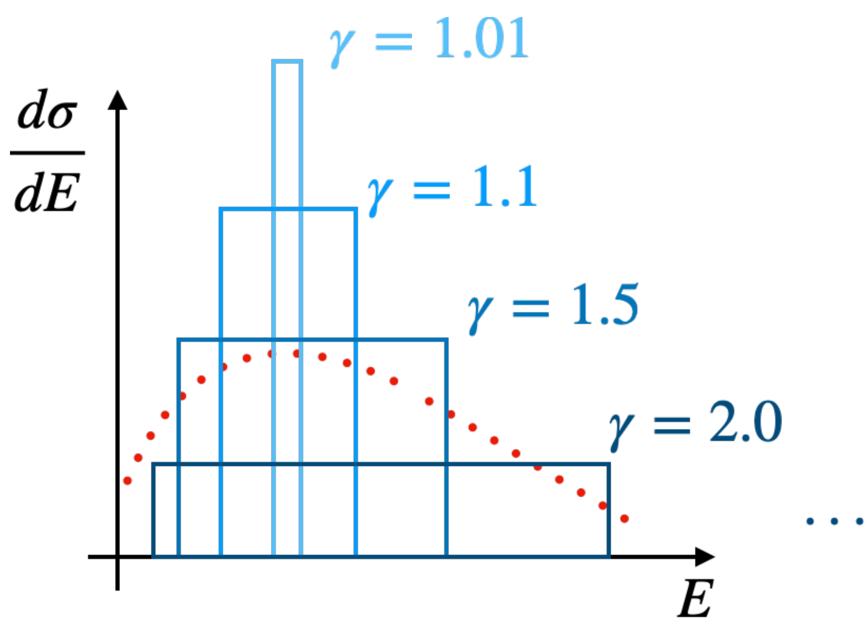




A subtle point of invariance

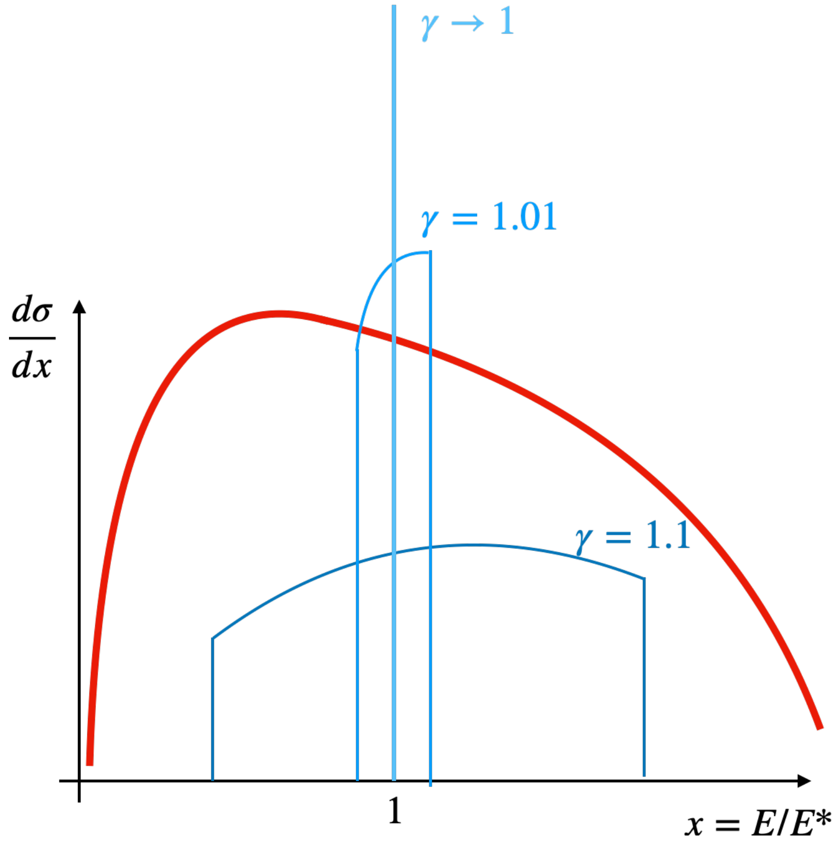
- Remember the famous π^0 decay…



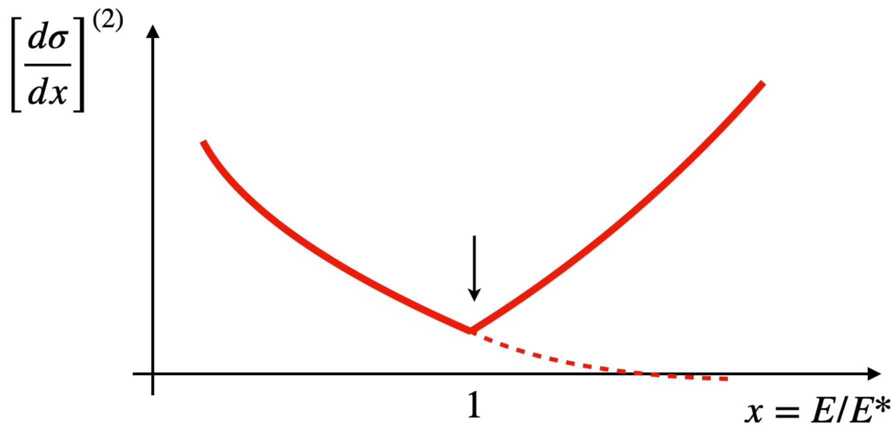


A subtle point of invariance

JHEP 05 (2019) 044



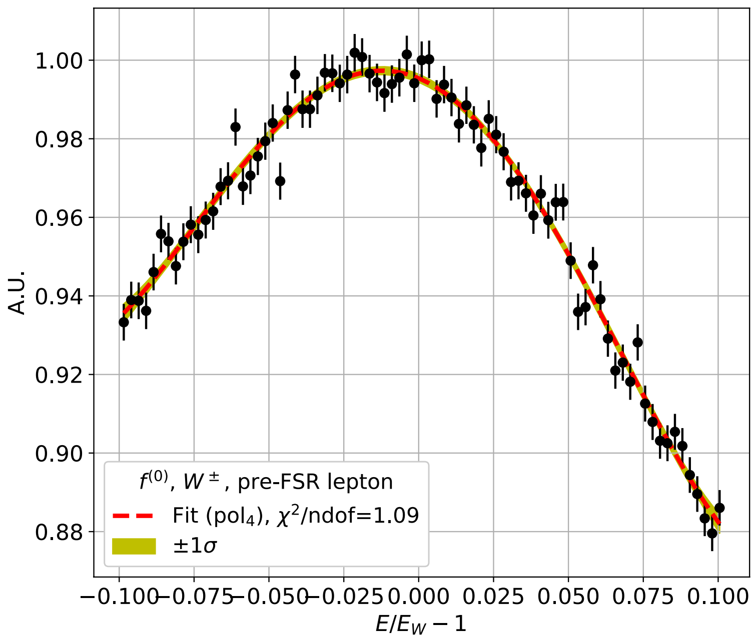
- What about a spin-1 particle?
  - "footprint" (kink) in the second-order derivative $f^{(2)}$ of the **energy spectrum**
    ➔ Lorentz-invariant estimator of M_W



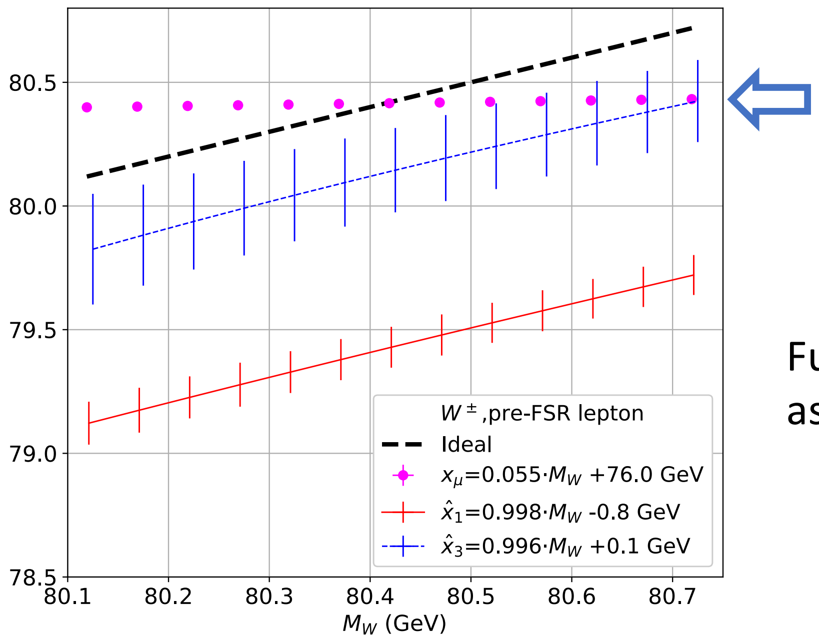
JHEP 05 (2019) 044

An energy-only M_W measurement?

E-spectrum fit to 4th order polynomial.
Take root of 3rd-order derivative ($\hat{x}_3$)



MC calibration needed to account for finite-width and QED radiation



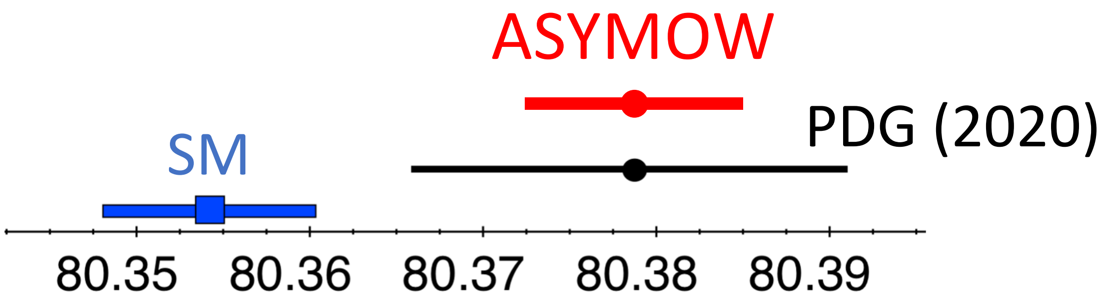
~**15 MeV** (stat.) feasible with full LHC data.

Further studies needed to assess feasibility.

Conclusions

- Three ways towards a precision measurement:
  - enhancements to theory models,
  - enhancements to the experiments,
  - a *Third Way*:
    - Novel
    - Challenging
    - Competitive

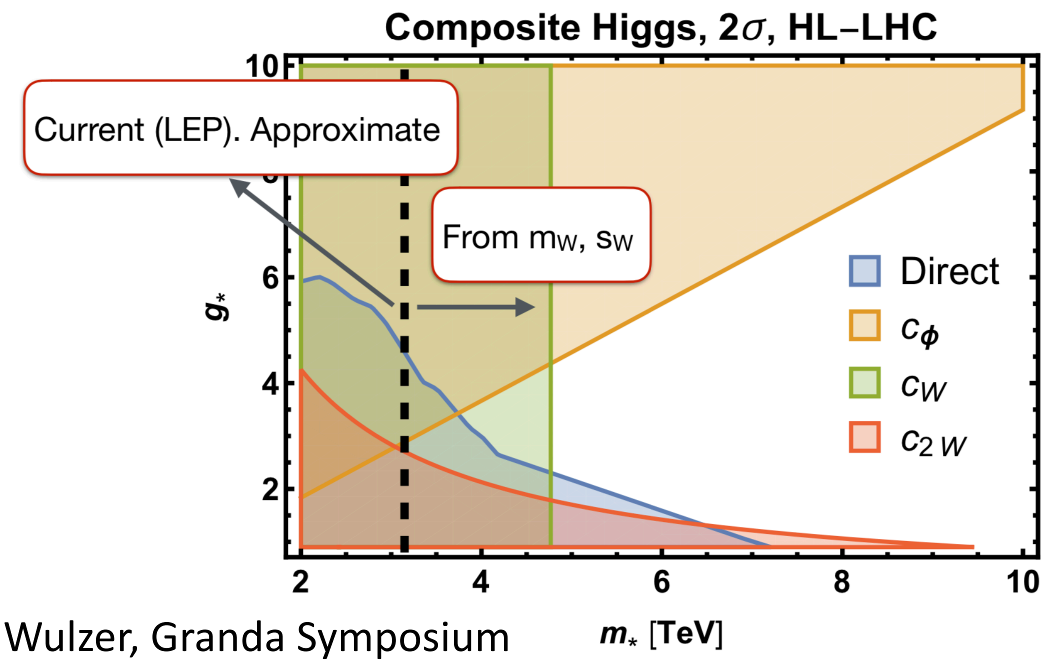
A project for the next years!



Grazie per la vostra attenzione!

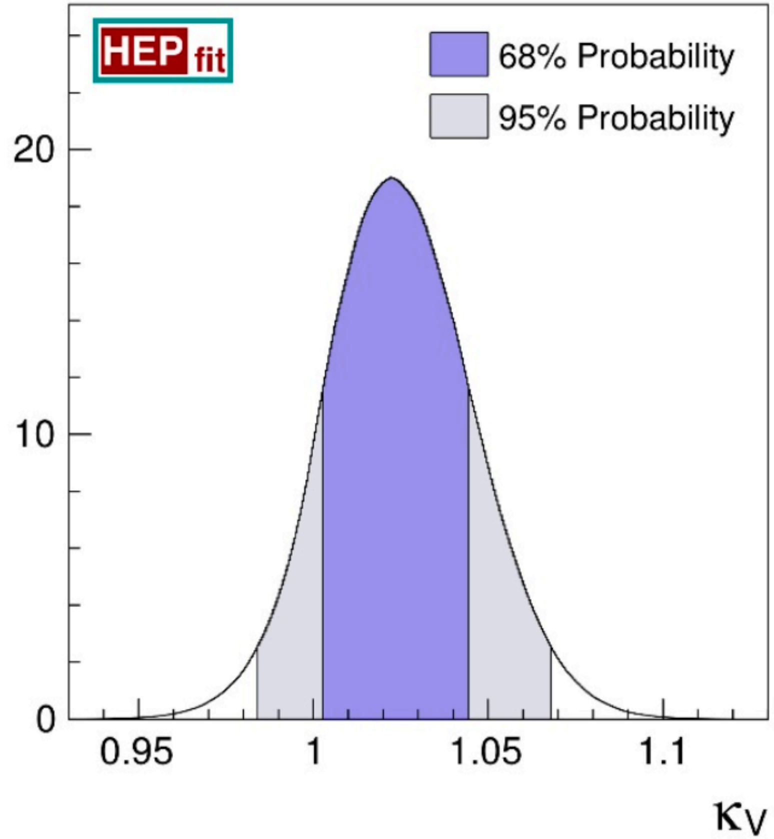
Cosa possiamo imparare da mW

- Interpretazione in modelli specifici
  - complementarietà con misure dirette (e.g. sez. d'urto dell'Higgs)



A. Wulzer, Granda Symposium

JHEP12 (2016) 135

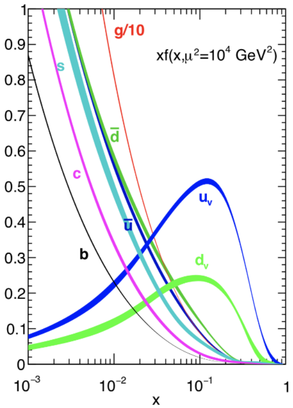


Predizione teorica

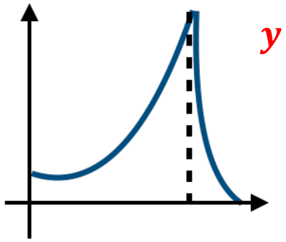
$$80.3535 \pm 0.0027_{m_t} \pm 0.0030_{\delta_{\text{theo}} m_t}$$
$$\pm 0.0026_{M_Z} \pm 0.0026_{\alpha_S}$$
$$\pm 0.0024_{\Delta\alpha_{\text{had}}} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\text{theo}} M_W}$$

The PDF uncertainty

Marginalize over
all $\boldsymbol{y}$ values and
q $(\bar{q})$ pairs

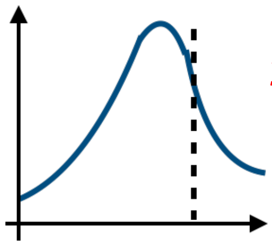


$u\left(\frac{Q}{\sqrt{s}}e^{+y_1}\right)\bar{d}\left(\frac{Q}{\sqrt{s}}e^{-y_1}\right)\times$



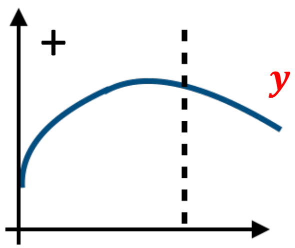
$\boldsymbol{y = y_1}$

$u\left(\frac{Q}{\sqrt{s}}e^{+y_2}\right)\bar{d}\left(\frac{Q}{\sqrt{s}}e^{-y_2}\right)\times$



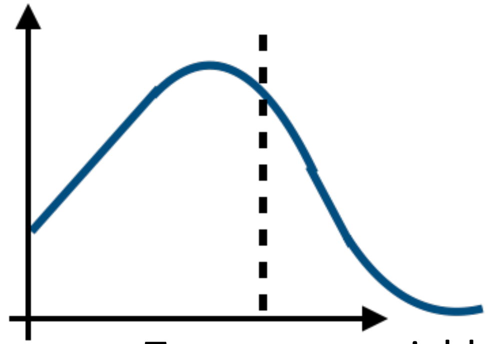
$\boldsymbol{y = y_2}$

$\bar{d}\left(\frac{Q}{\sqrt{s}}e^{+y_2}\right)u\left(\frac{Q}{\sqrt{s}}e^{-y_2}\right)\times$



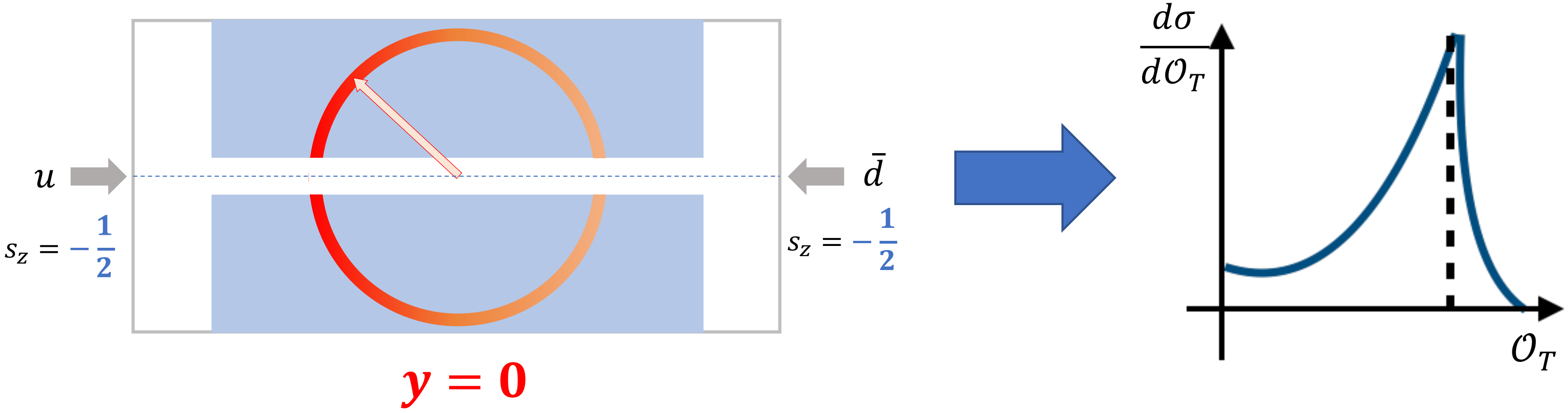
$\boldsymbol{y = \cdots}$

... ...



The PDF uncertainty

- Why then longitudinal dynamics also matters?
  - Mostly an **acceptance** artefact



The PDF uncertainty

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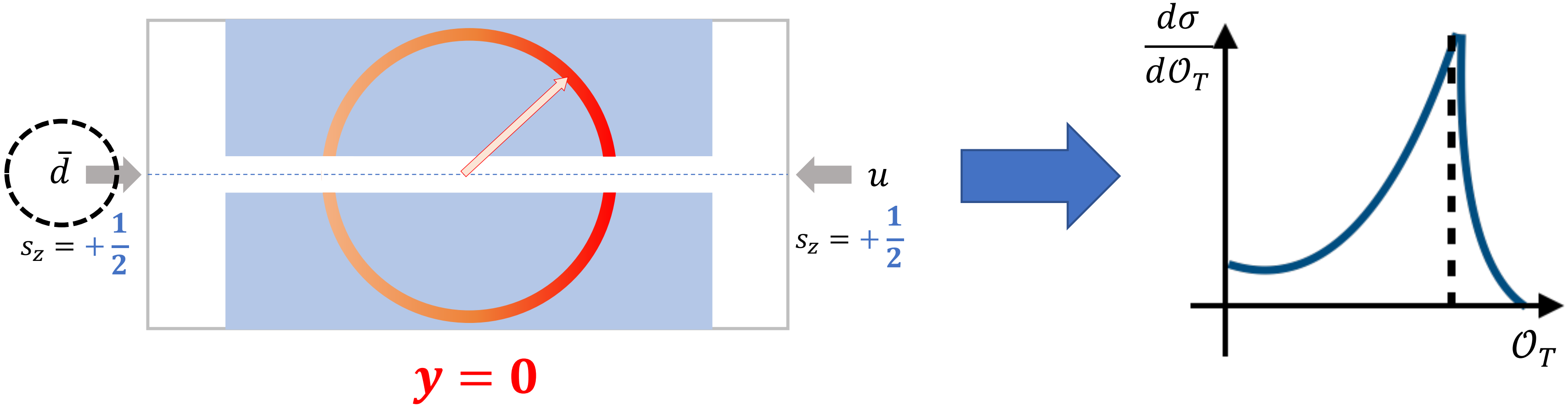
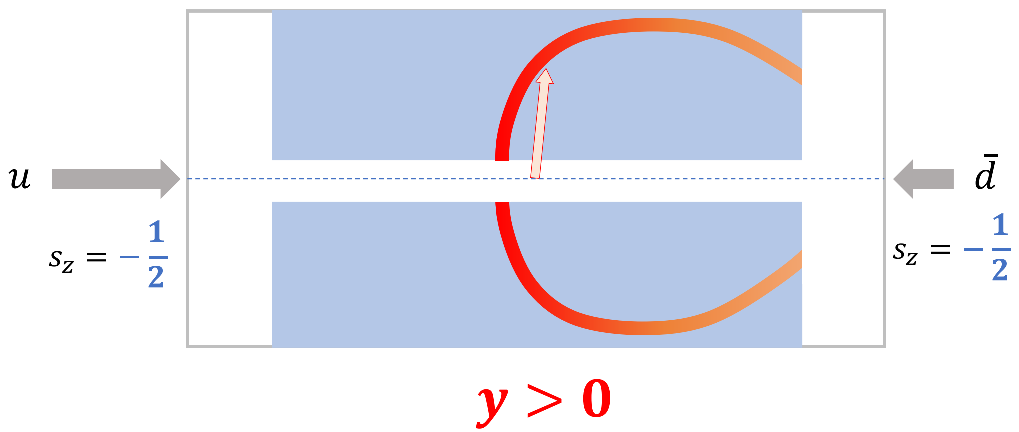
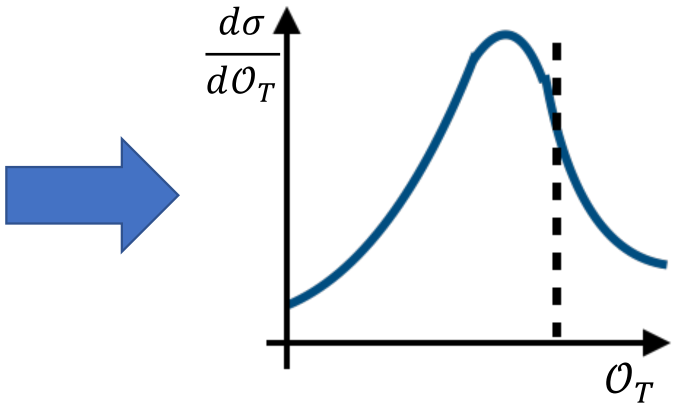


➔ Invariant under $q \leftrightarrow \bar{q}$

The PDF uncertainty

- Why then longitudinal dynamics also matters?
  - Mostly an **acceptance** artefact

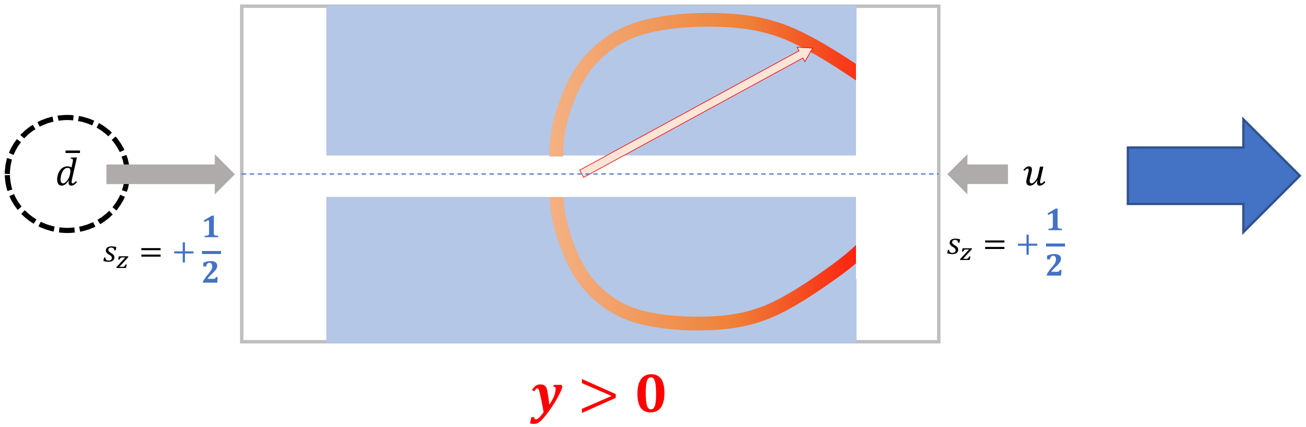


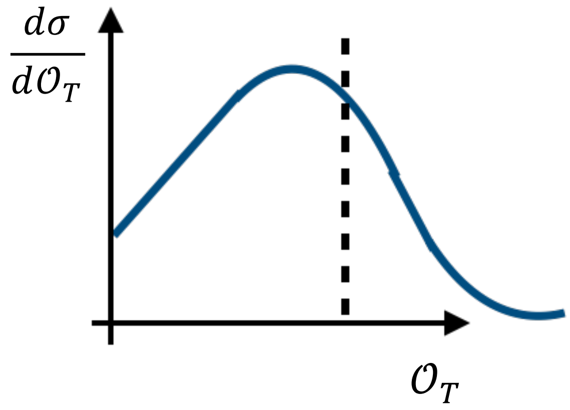


➔ Sculpted by the detector

The PDF uncertainty

- Why then longitudinal dynamics also matters?
  - Mostly an **acceptance** artefact

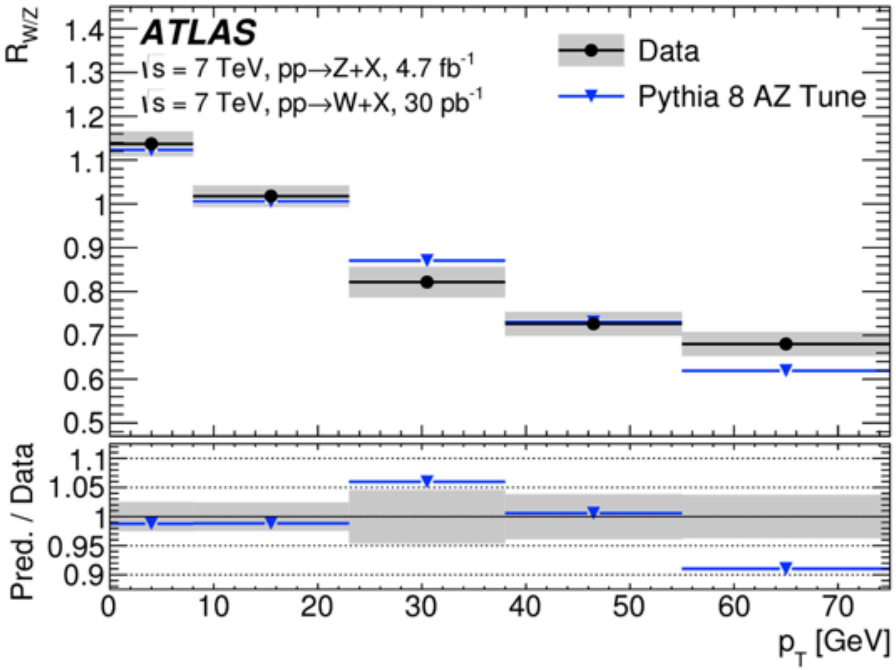




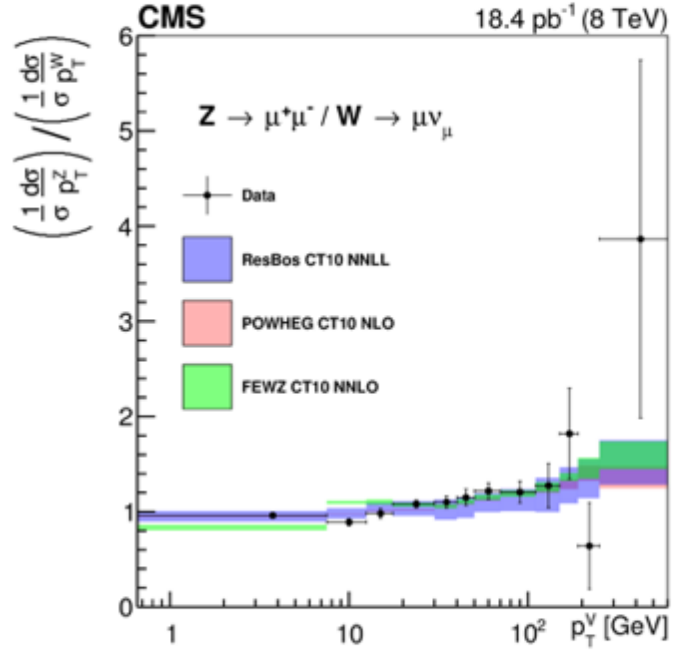
➔ Different under $q \leftrightarrow \bar{q}$

Measurements of q_T spectra

PRD 85 (2012) 012005

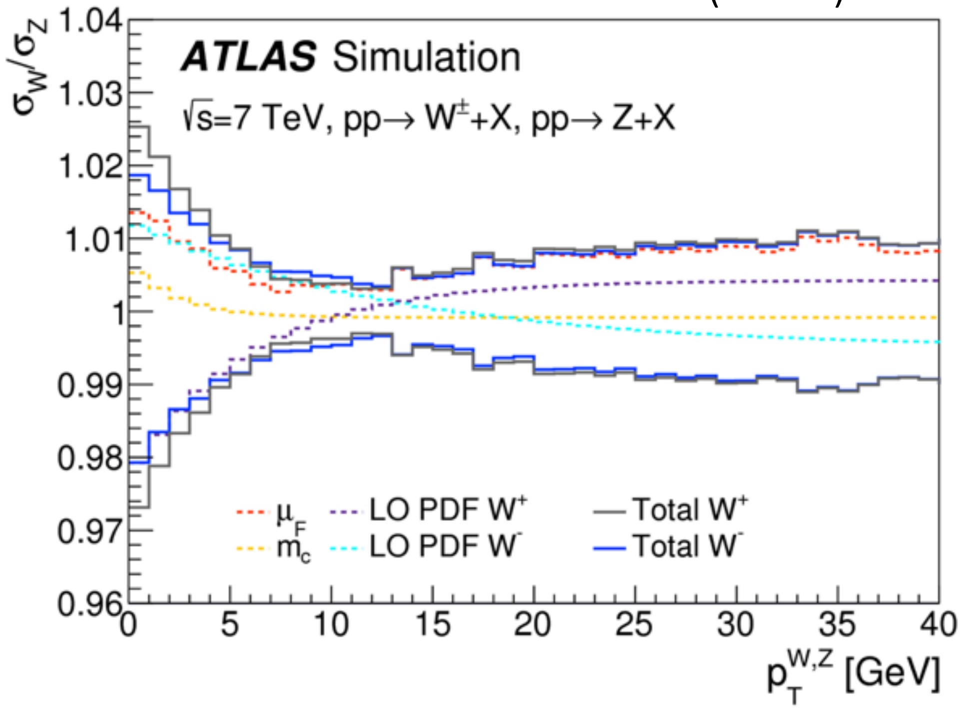


JHEP 02 (2017) 096

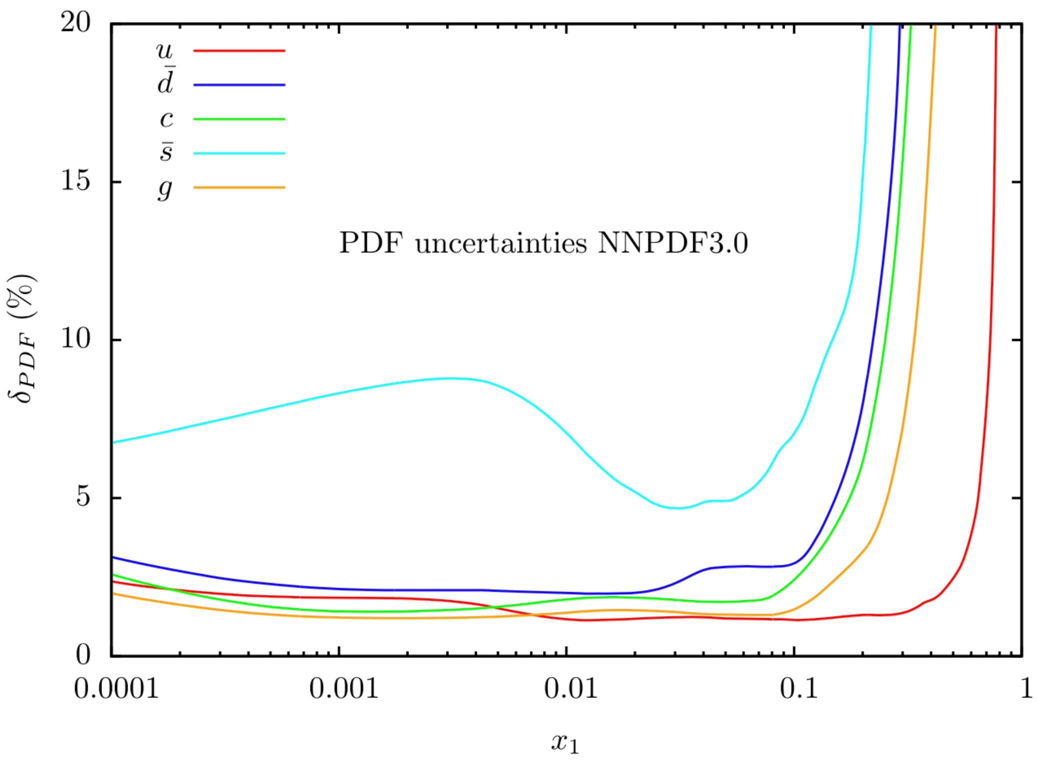


Measurements of q_T spectra

EPJC 78 (2018) 110



PDF uncertainty vs acceptance



PRD 91 (2015) 113005

Normalized distributions			
Cut on $p_\perp^W$	Cut on $\lvert\eta_l\rvert$	CT10	NNPDF3.0
Inclusive	$\lvert\eta_l\rvert < 2.5$	$80.400 + 0.032 - 0.027$	80.398 ± 0.014
$p_\perp^W < 20$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.396 + 0.027 - 0.020$	80.394 ± 0.012
$p_\perp^W < 15$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.396 + 0.017 - 0.018$	80.395 ± 0.009
$p_\perp^W < 10$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.392 + 0.015 - 0.012$	80.394 ± 0.007
$p_\perp^W < 15$ GeV	$\lvert\eta_l\rvert < 1.0$	$80.400 + 0.032 - 0.021$	80.406 ± 0.017
$p_\perp^W < 15$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.396 + 0.017 - 0.018$	80.395 ± 0.009
$p_\perp^W < 15$ GeV	$\lvert\eta_l\rvert < 4.9$	$80.400 + 0.009 - 0.004$	80.401 ± 0.003
$p_\perp^W < 15$ GeV	$1.0 < \lvert\eta_l\rvert < 2.5$	$80.392 + 0.025 - 0.018$	80.388 ± 0.012

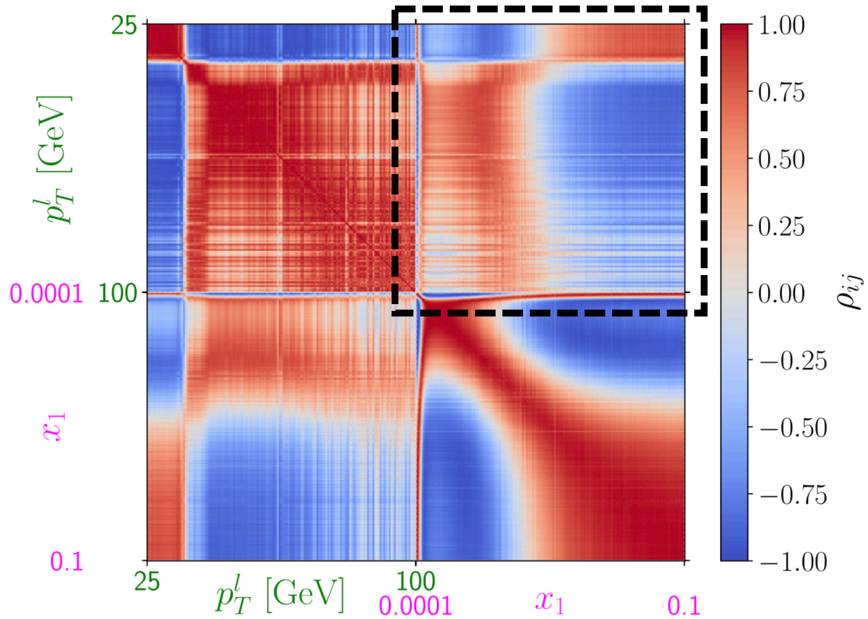
PRL 126 (2021) 041801

A new look at PDF uncertainty

- p_T^l **spectrum alone** enough to constrain all the PDF uncertainty at high lumi
  - Just use correlation pattern with p_T^l

$$\chi^2_{k,\min} = \sum_{(r,s)\in \text{bins}} (\mathcal{T}_{0,k} - \mathcal{D}^{\text{exp}})_r (C^{-1})_{rs} (\mathcal{T}_{0,k} - \mathcal{D}^{\text{exp}})_s$$

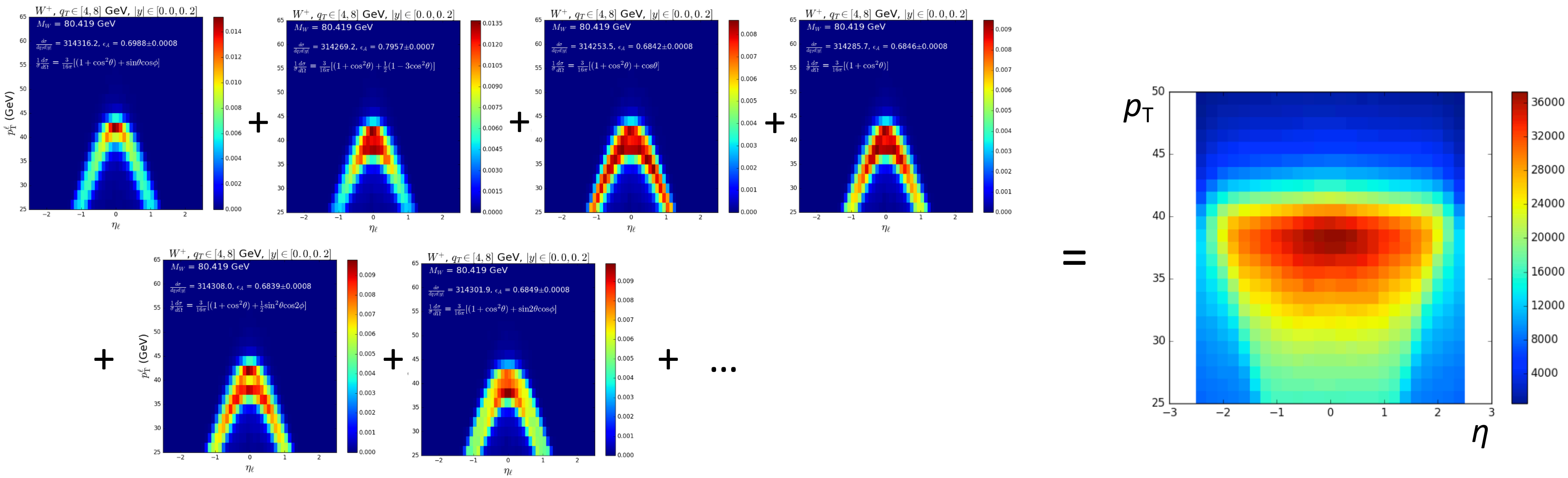
➔ $\delta_{\text{PDF}} \to$ 1 MeV with 300/fb!



- Looser constraints when detector included
  - Also handling of q_T not straightforward in this setup

Towards an agnostic model

- From Eq. **[1]**: joint p.d.f. (p_T, η) as a linear combination of a finite and complete set of <u>templates</u>:



Master formula for spin-1 energy spectrum

$$f(x) = \int \frac{dy}{y}\, h(y) \int_{\frac{1}{2}\left(\frac{x}{y}+\frac{y}{x}\right)}^{+\infty} d\gamma\, g(\gamma)$$
$$\times\ \frac{3}{8}\left[\frac{1+\frac{1}{2}A_0(\gamma)}{(\gamma^2-1)^{\frac{1}{2}}} + \frac{A_4(\gamma)}{(\gamma^2-1)}\left(\frac{x}{y}-\gamma\right) + \frac{1-\frac{3}{2}A_0(\gamma)}{(\gamma^2-1)^{\frac{3}{2}}}\left(\frac{x}{y}-\gamma\right)^2\right]$$

$$f(1+\epsilon) \approx A + B\epsilon + C|\epsilon| + D\epsilon^2 + E|\epsilon|\epsilon + F\epsilon^3 + G|\epsilon^3| + H\epsilon\ln|\epsilon| + \mathcal{O}(\epsilon^3)$$

Testing on MC