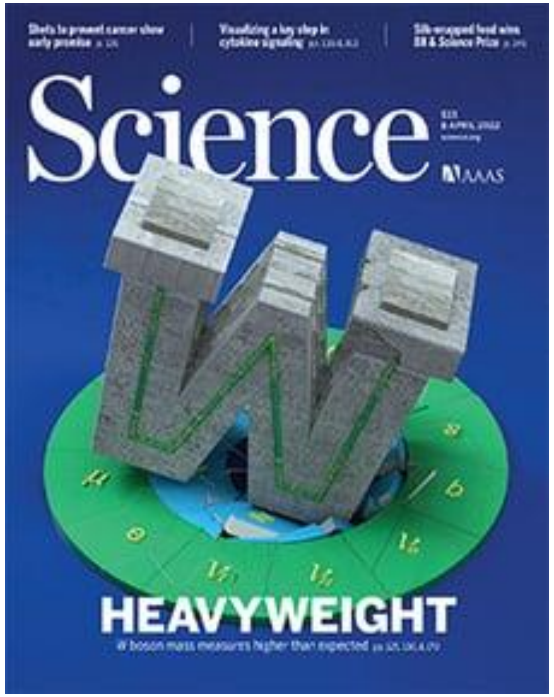
CDF II におけるW ボソン質量の精密測定
-　ATLAS 測定と比較しながら -



Contents:
- W 質量測定の概要
  - 運動量、エネルギースケール
  - QCD成分(⇒ν運動量)の評価
- 質量測定結果
- ~~Implications of new W mass- quick~~
- Summary

CDF II: Science 376, (2022)　170 and Suppl.Material
ATLAS: Eur. Phys. J. C 78 (2018) 110

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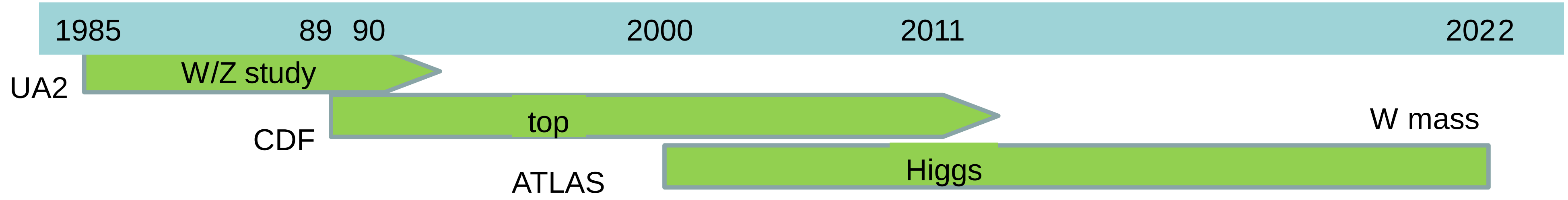
略歴

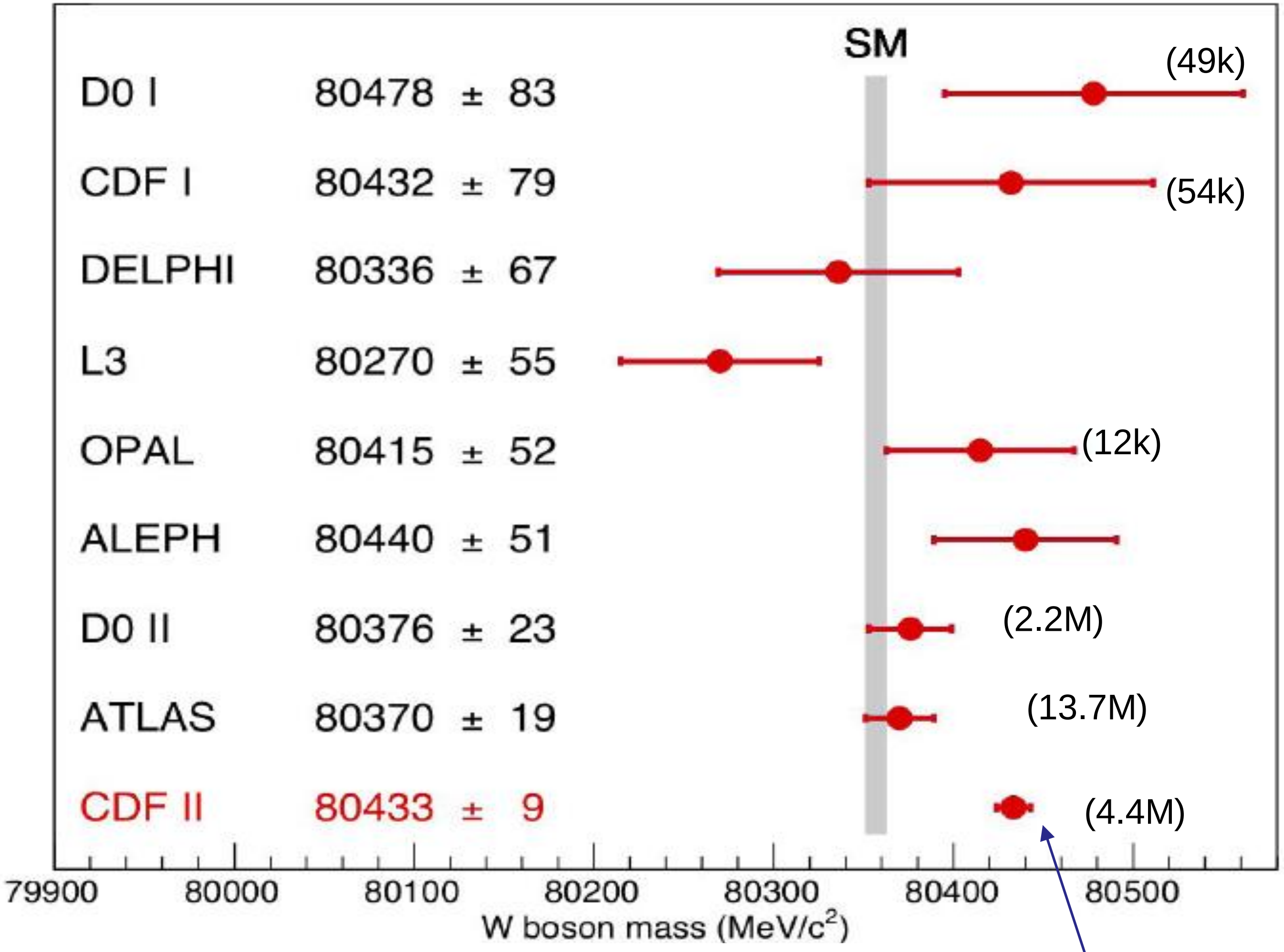


W mass: history

Science

SM expectation (PDG2020)

$M_W = 80,357 \pm 6\ \mathrm{MeV}$

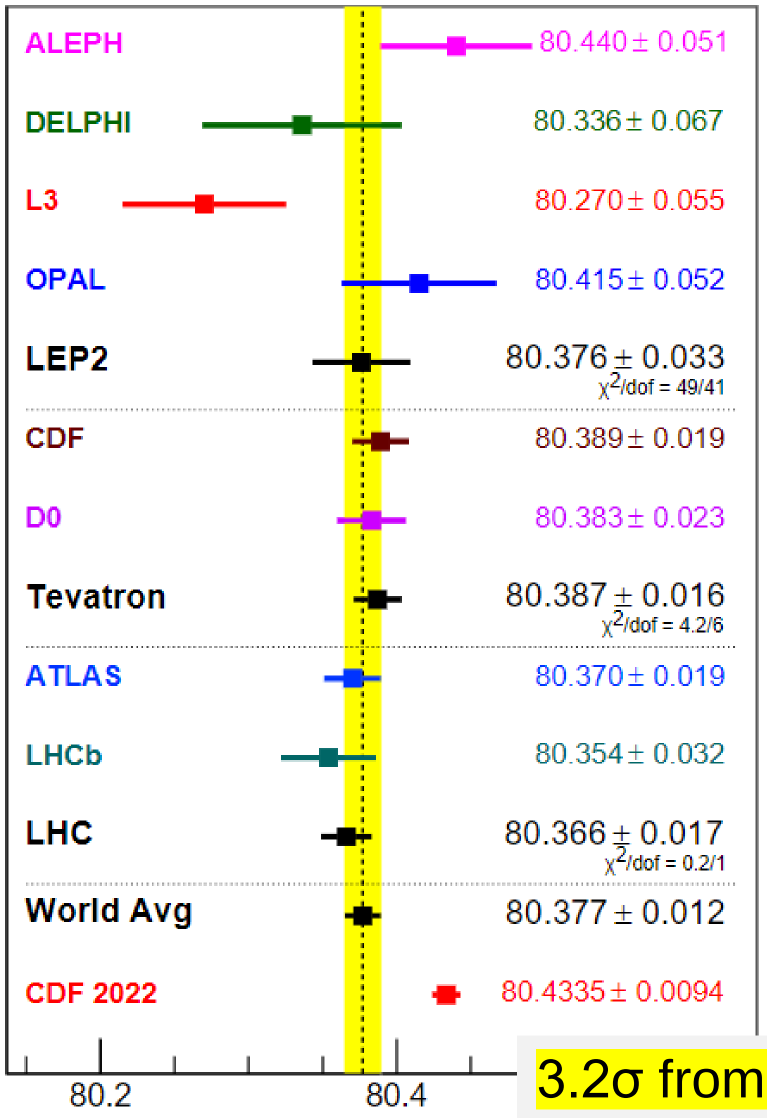


7σ from SM

$M_W = 80,433.5 \pm 9.4\ \mathrm{MeV}$

PDG2022

WA (excl. CDF2022)



(1.1M)

(4.4M)

3.2σ from WA

- +46 MeV from prev. CDF
- +74 MeV(3.0σ) from ATLAS

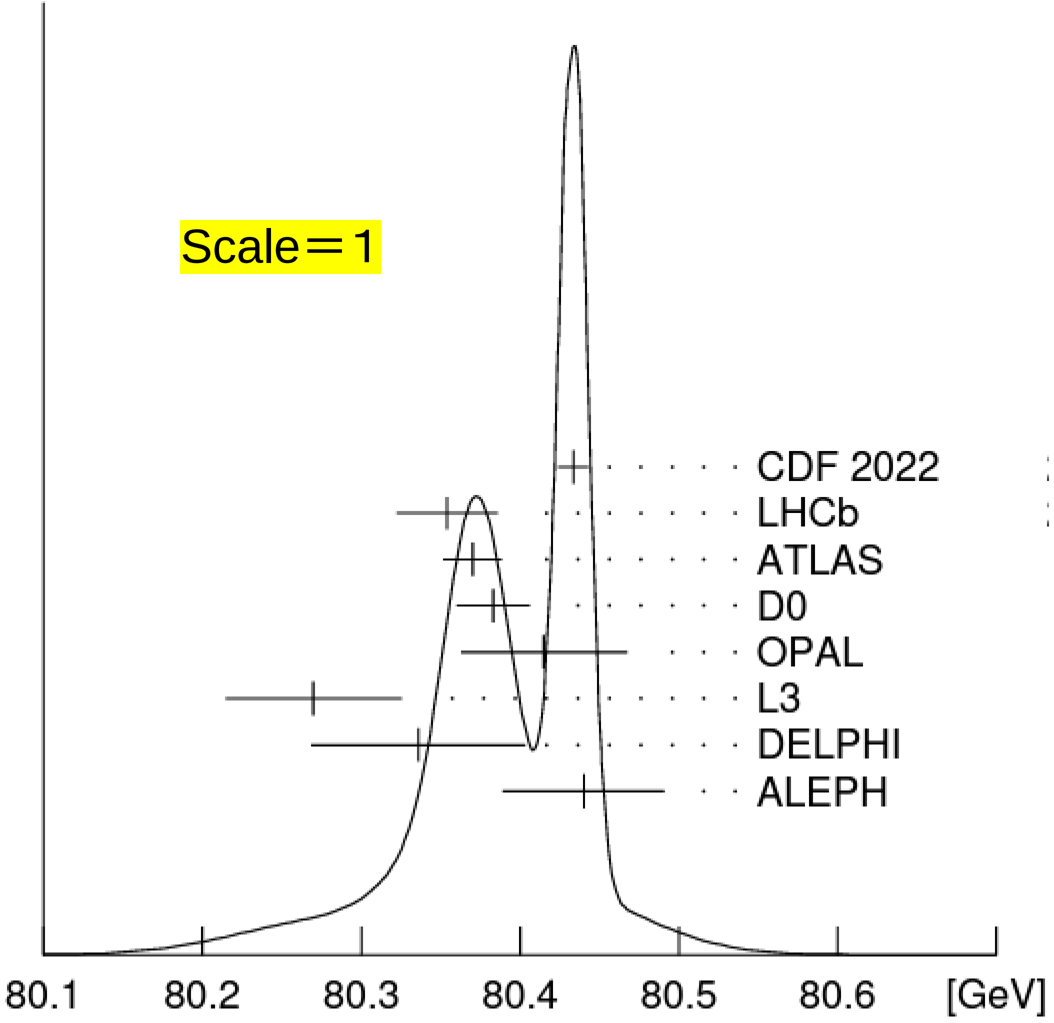
W mass: PDG2022

W mass (2022) 80.377 ± 0.012 GeV

CDF2022を加えると中心値は約40MeV大きくなる
χ^2/NDF～1には各実験の不確かさを2倍にする必要

CDF2022は中心値計算に入れていない

測定値の相関



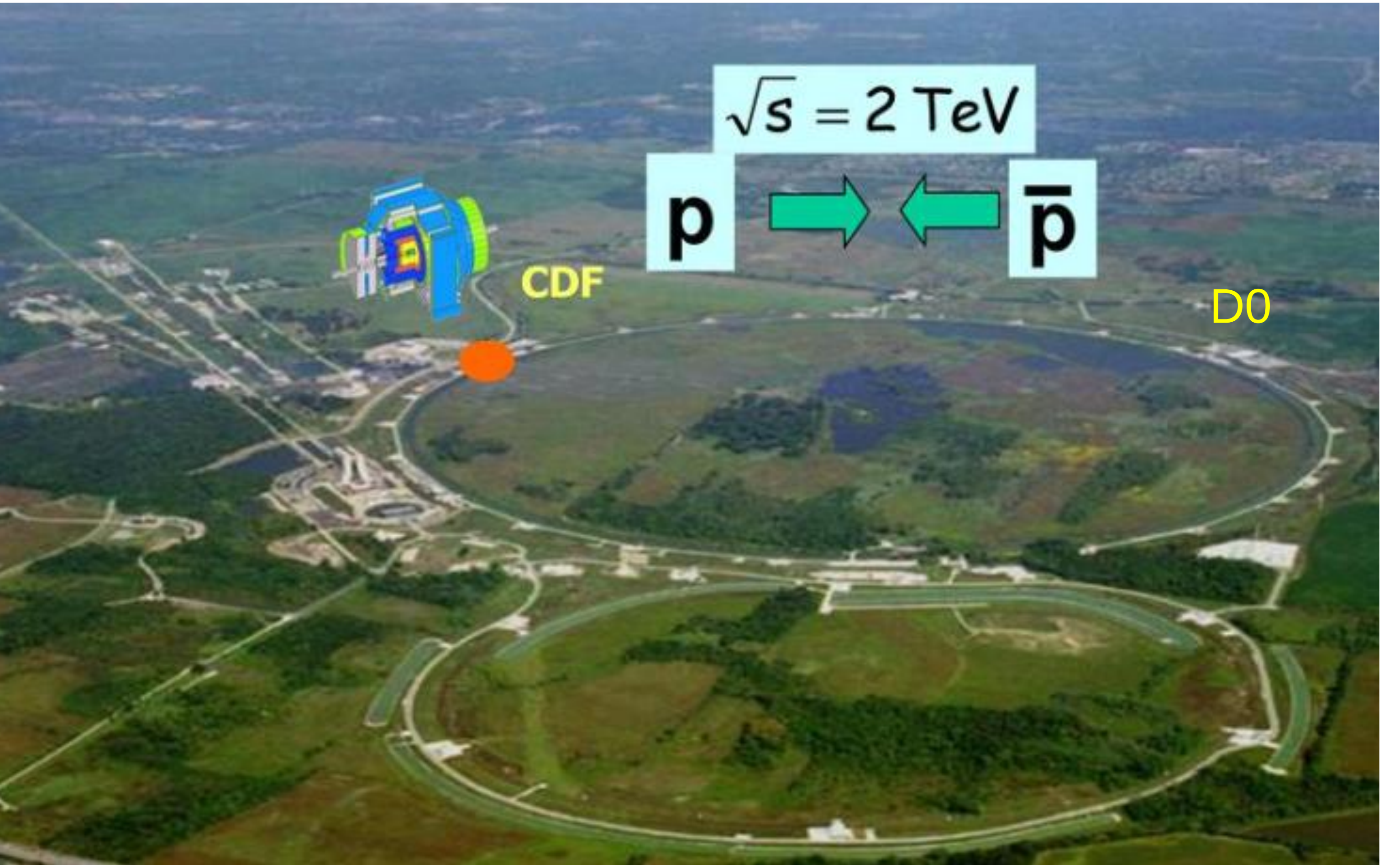
原さんへ
New "scale-factored" world average of mW のreferencesは次のようです。
(1) G. Wilson's talk at ECFA Higgs Factory seminars:
Precision physics in the e+e- -> WW region, June 10 2022:
https://indico.cern.ch/event/1163667/
(2) S. Heinemeyer's talk at IDT-WG3-Phys Open Meeting on mW , 12 May 2022:
https://agenda.linearcollider.org/event/9357/

CDF Experiment

25年にわたる
エネルギー最
前線の実験

Fermilab Tevatron (1.8 (Run1) → 1.96 (Run2) TeV $p\bar{p}$ Collider)

70km west of Chicago



Brief History

1980: US-Japan-Italy Collab.

1985 October: 1st collision

1988 W paper*1

1994: evidence of top

1995: discovery of top (w/ DO)

2006: Bc, Λc discovery

(2009 LHC first collision)

2011: Tevatron shutdown

2012: W paper (1/4 of Run2 data)

2022: most precise W mass *2

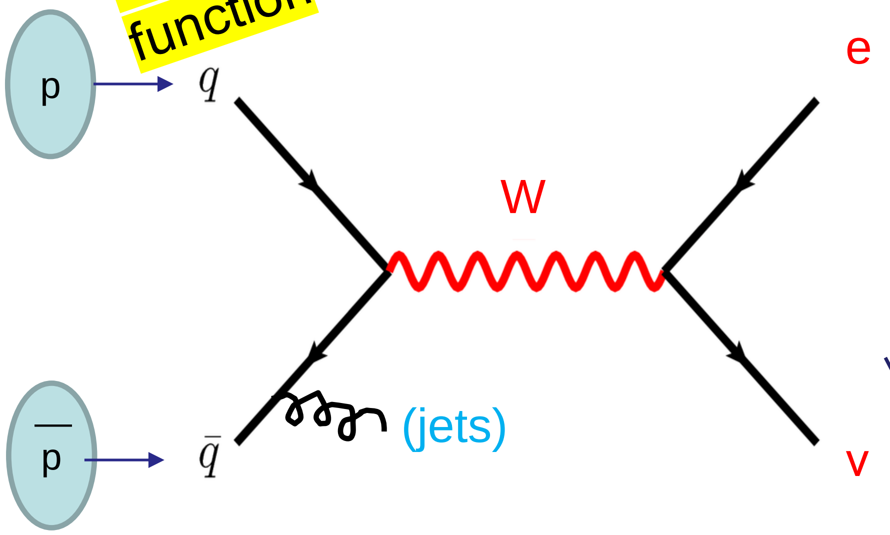
25 years

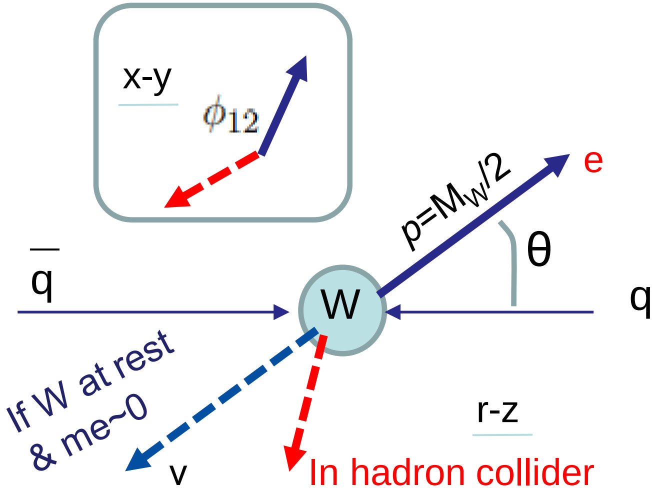
*1 3 Nations 18 Institutes 191 Authors

*2 14 Nations 73 Institutes 381 Authors

W mass measurement: key points

(0) PDF: parton distribution function





Lepton (e/μ) momentum/energy測定
(1) ←検出器応答のcalibration

Neutrino momentum は "missing" 成分として推定できる

- z方向の初期/最終運動量は決まらない
- p_TバランスもW粒子以外の成分(=jets)の生成で崩れる

(2) ←より多くの成分(jet)を測定する
← QCD 生成を理解する
(Physics modelling)

W-mass測定に用いられる分布*

$$p_T = p \sin\theta$$

- Charged Lepton (=e/μ) transverse momentum
- Neutrino transverse momentum
- Transverse mass (no *z* components used)

*ハドロン衝突器ではneutrino p_z を測定できないために、不変質量を計算できない

$$M_T^2 = m_1^2 + m_2^2 + 2\left(E_{T,1}E_{T,2} - \vec{p}_{T,1}\cdot\vec{p}_{T,2}\right)$$

for $m_1 = m_2 = 0$　　with $E_T^2 = m^2 + (\vec{p}_T)^2$

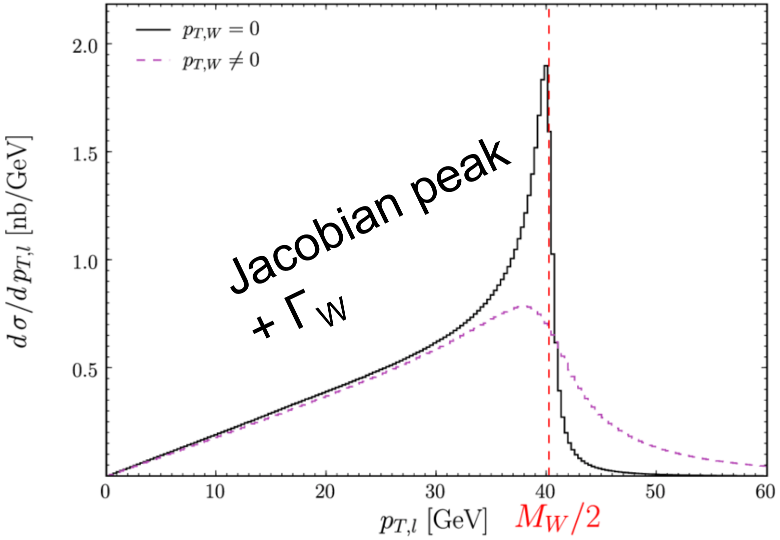
$$M_T = \sqrt{2\left(p_T^\ell p_T^\nu - \vec{p}_T^{\,\ell}\cdot\vec{p}_T^{\,\nu}\right)}$$

$$= \sqrt{2\,p_T^\ell p_T^\nu\,(1-\cos\phi_{12})}$$

More about transverse mass

if p_T^W=0

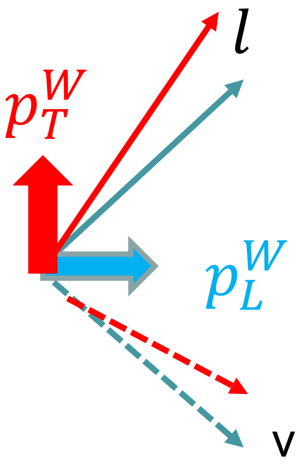
$$p_T^l = (M_W/2)\sin\theta$$



$$\frac{d\sigma}{dp_t} = \frac{d\sigma}{d\cos\theta} * \frac{d\cos\theta}{dp_t} = \frac{d\sigma}{d\cos\theta} * \frac{2p_t}{M_W} * \frac{1}{\sqrt{(\frac{M_W}{2})^2 - p_t^2}}$$

$$M_T = \sqrt{2\, p_T^{\ell} p_T^{\nu}\, (1 - \cos\phi_{12})}$$

も M_W をJacobian peakとして分布する



if $p_T^W \neq 0$

p_T^l : p_T^W により直接影響を受ける　CON

M_T : p_T^W の効果は p_T^W/M_W の程度　PRO

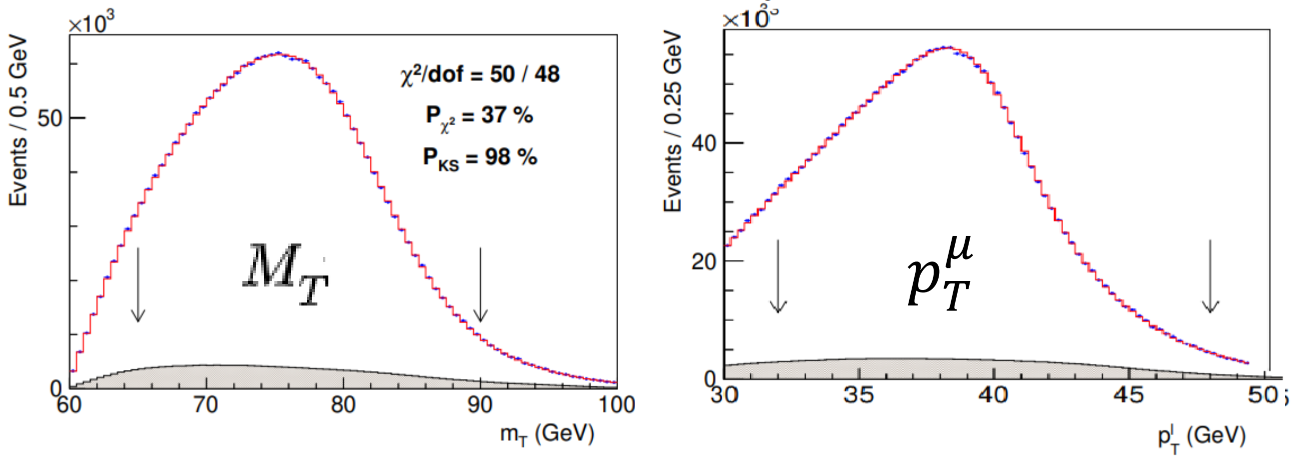
p_T^ν (=recoil QCD activity)を知る必要　CON

M_T の方が p_T^W が小さい条件で p_T^W modelingへの依存性を小さくできる

$|\vec{u}| < 15$ GeV　CDF

$u_T < 30$ GeV　ATLAS

CDF2022 での実際の分布

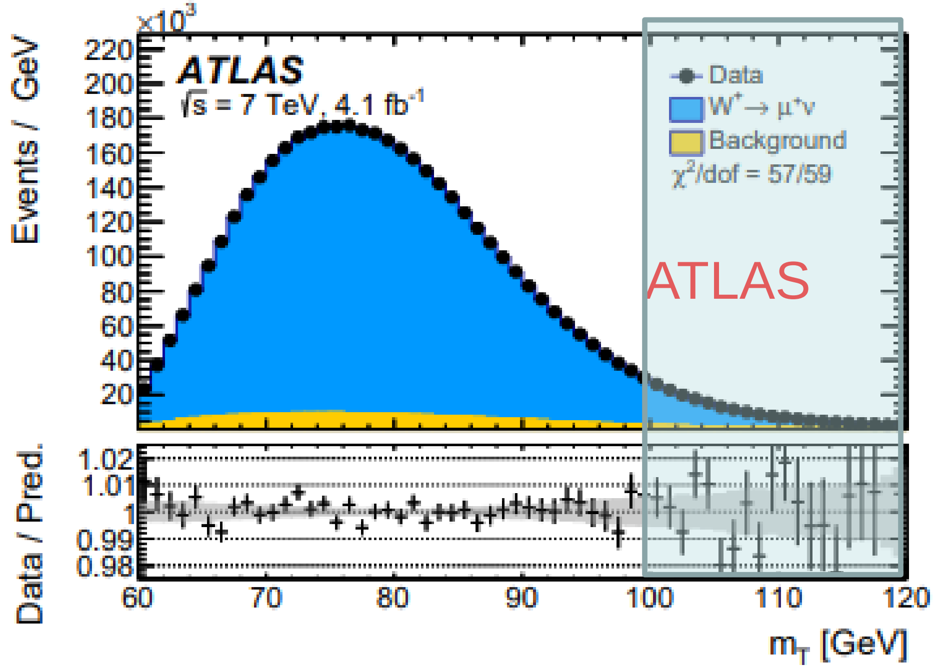


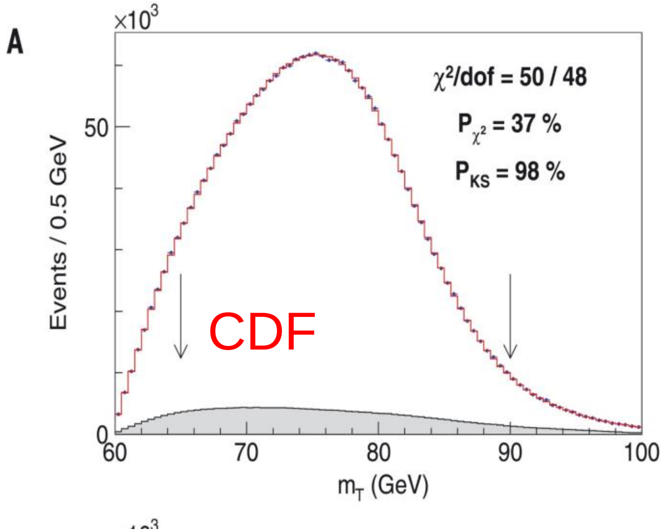
“Advantage” of W mass measurement with CDF

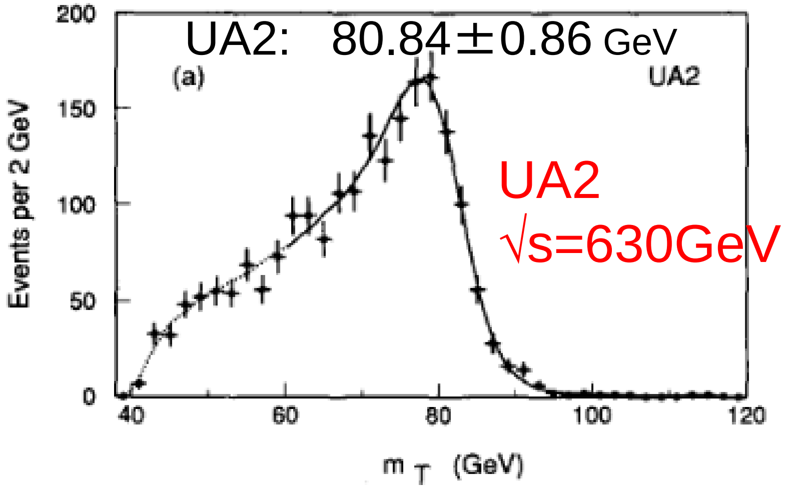
Tevatron: proton-antiproton collider@1.96TeV,8.8/fb, 2.4/1.8x10^6 Ws (μ/e)

LHC: proton-proton collider@7TeV, (ATLAS) 4.6/fb, 7.8/5.9x10^6 Ws (μ/e)

✓ LHC: 生成断面積が大きい







✓ LHC: transverse activityが高い ☞ M_T distribution はより “dilute”

✓ LHC: longitudinal activityが高い ☞ Wはより前方にも発生する

✓ LHC: 反クォークのPDF不定性が大きい☞ p_T^W, QCD activity の不定性が大きい

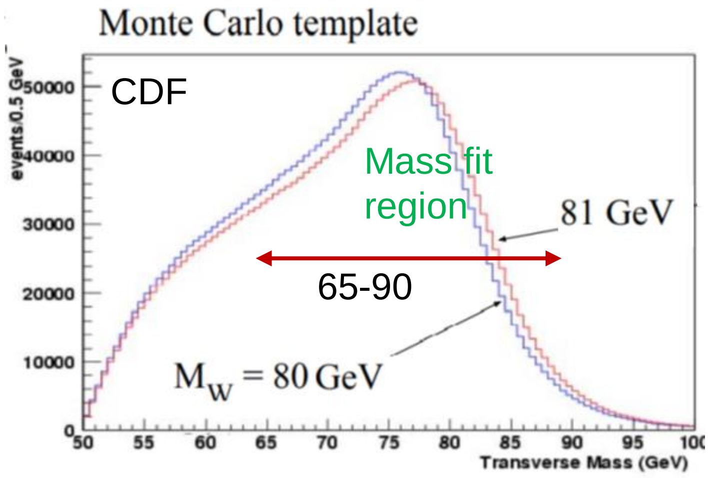
Signal shape and template fitting

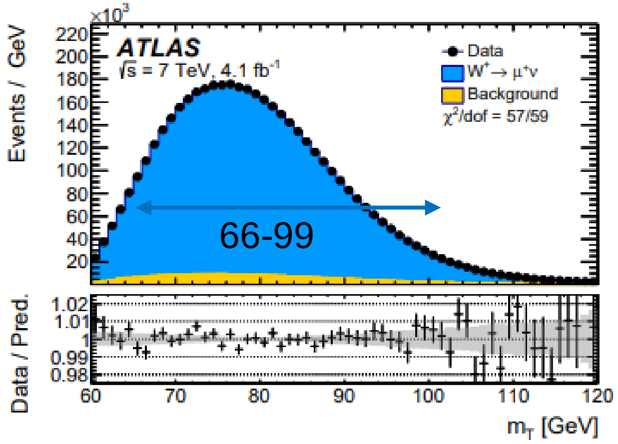
W-mass測定に用いられる分布

- Charged Lepton transverse momentum
- <Neutrino transverse momentum>
- Transverse mass

X (e, μ) = **6** 個の分布 by **CDF**
= 4 個の分布 by ATLAS(ν p_Tは使わない)

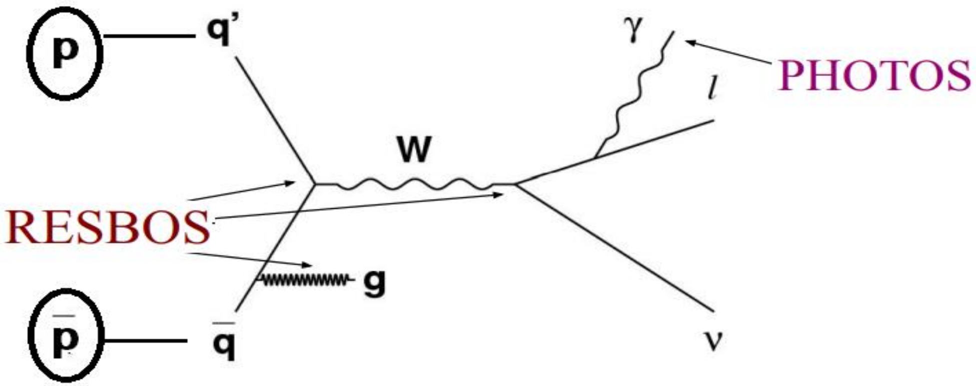
M_W を変えて分布をシミュレートする
⇒ 測定値に最も合致する分布から M_W





Simulation modelling

PDF: NNPDF3.1,CT10,.. /CT10, CT14,.. - NNLO



CDF: ~80% collision of valence quarks
ATLAS: 0%

NLO Powheg+Pythia8

- CDF:RESBOS/DYqT+PHOTOS のparameters を Z や W のdata分布を用いて決定する
- ATLAS: (NLO) Powheg+Pythia8 event generator を用い、event毎に高次補正を勘案したweightをかける (parameters は Z や W data分布を用いて決定)

要点:Lepton (e, μ) energy scales/acceptance/efficiency
⇒ 検出器応答を可能な限り正確に理解する
⇒ Simulation parameters ⇒ data分布を用いてtune

Lepton coverage

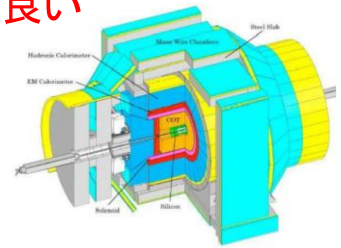
ATLAS は前方η 領域まで、いくつかの要素からなる検出器を使用

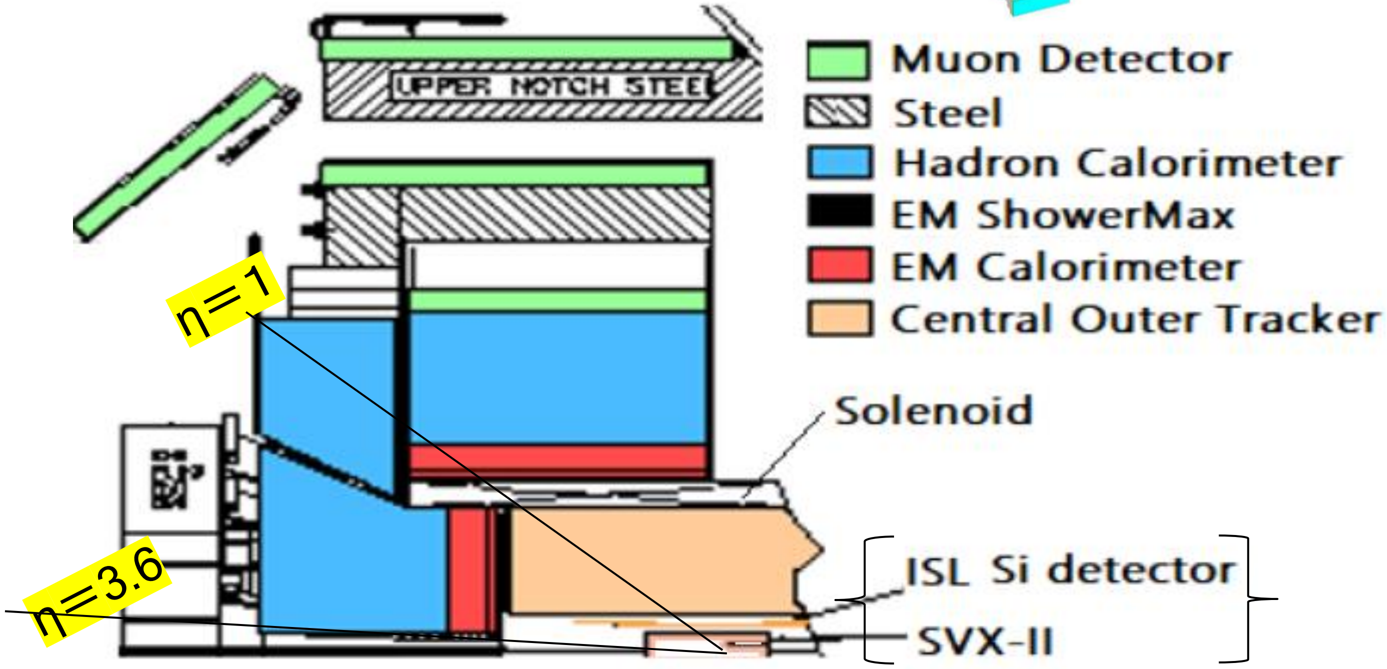
e: $|\eta| < 2.4$ (exclude $1.2 < |\eta| < 1.82$)
μ: $|\eta| < 2.4$ ID+MS で同定=> ID だけで運動量

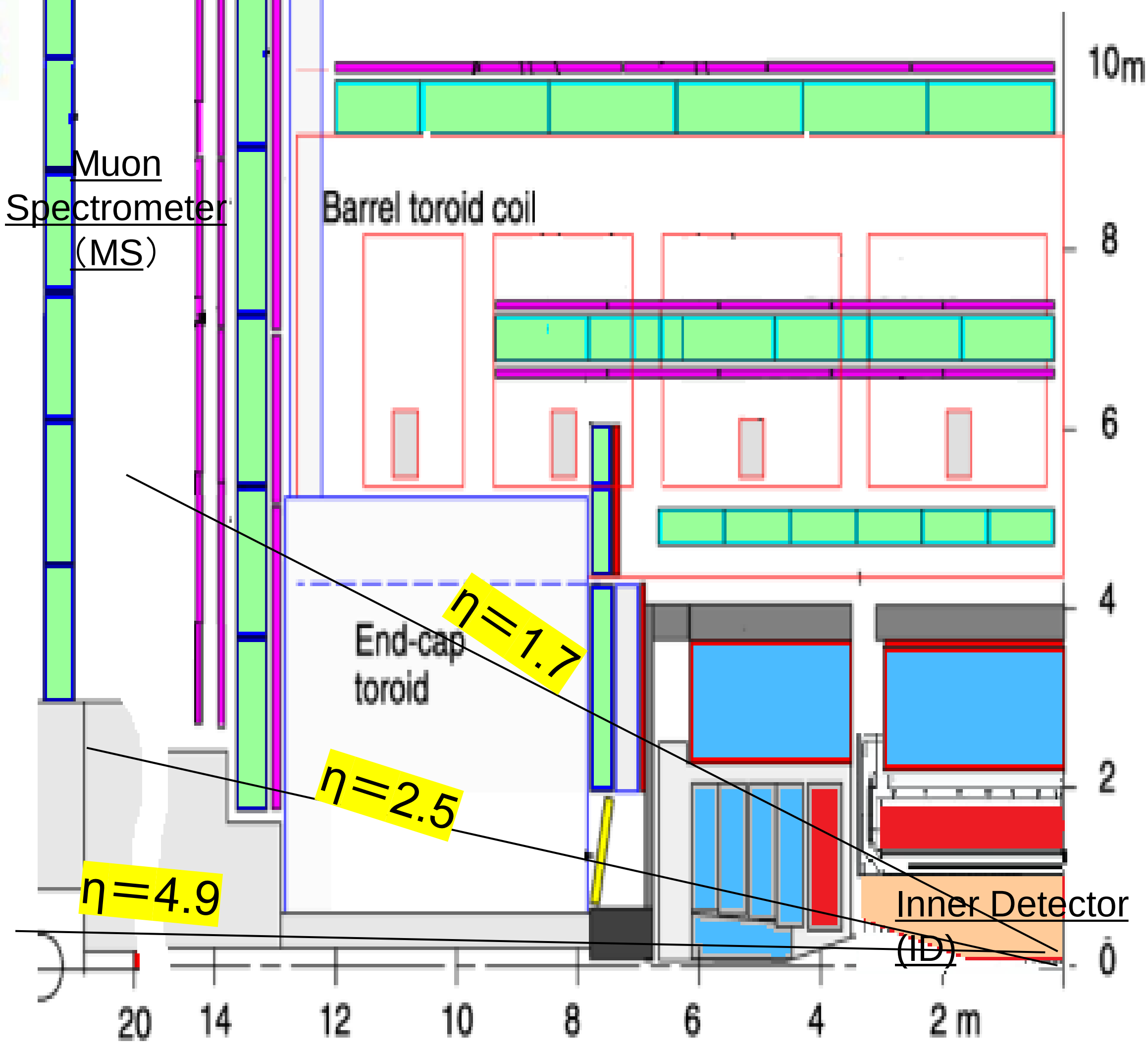
pseudorapidity $\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$

CDF は用いる検出器が単一で一様性が良い

Use **Central leptons |η|<1**





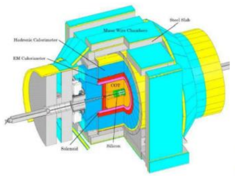


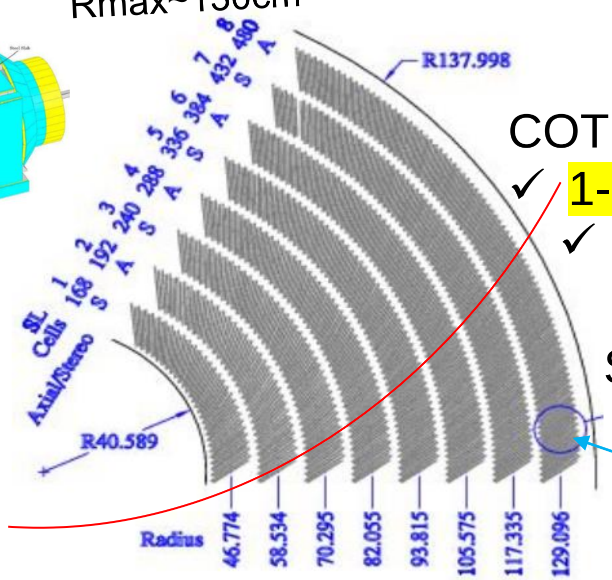
(1) CDF charged lepton E&p measurement

(a) Muon momentum

p_T=0.3Bρ

Rmax~130cm





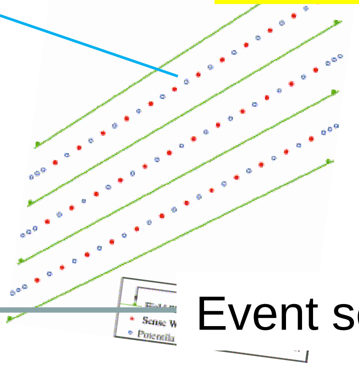
COT (drift wire chamber)のみ

✓ 1-1 Wire positions

✓ Precise B filed map (B=1.5T)

Scattering/radiation

✓ Precise material map



絶対値はJ/ψ,Y質量から決定

(b) Electron energy(+direction)

決定した運動量スケールpを用いて

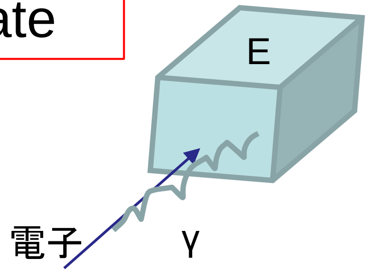
☞ 1-3 E/p matching でEをcalibrate

電子は物質によりγを放出しやすい:

Simulationを用いてE/p分布を再現

- 物質量分布
- calorimeter応答の一様性
- 電子に対する信号の形状

Electron radiation: PHOTOS/HORAGE

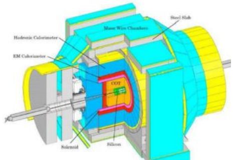


カロリメータセル分割 ΔηxΔφ ＝0.1x15°

Event selection:

Central leptons* |η|<1

*Use only well measurable COT



$$30 < p_T^\ell < 55\ \mathrm{GeV}$$

$$30 < p_T^\nu < 55\ \mathrm{GeV}$$

e: $|\eta| < 2.4$ (exclude $1.2 < |\eta| < 1.82$)

μ: $|\eta| < 2.4$ Id'ed w/ ID+MS => ID alone for kinematics

$$p_T^\ell > 30\ \mathrm{GeV}$$

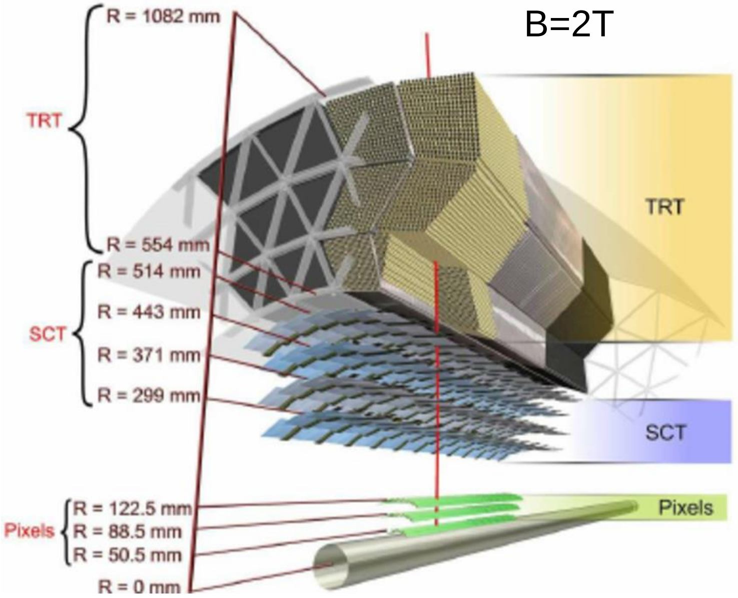
$$p_T^{miss} > 30\ \mathrm{GeV}$$

ATLAS

(1) ATLAS charged lepton E&p measurement

(a) Muon momentum

Rmax~100cm
B=2T

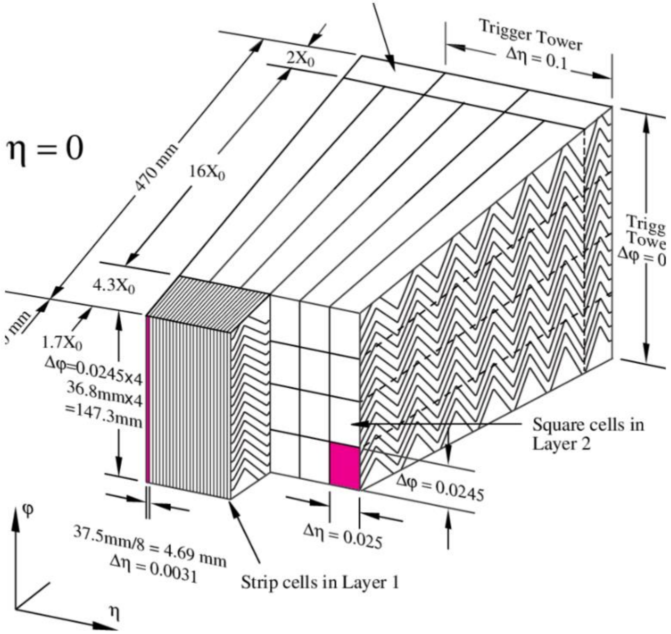


(b) Electron energy(+direction)

cell 毎の応答はmipやMCシミュレーション

☞energy sum in

$\Delta\eta \times \Delta\varphi = 0.075 \times 0.175$
(in central)



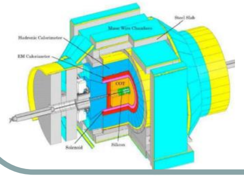
宇宙線やJ/ψ等で応答一様化調整をしたのちに、Z 質量を用いて校正

Smaller systematics

Event selection:

Central leptons* |η|<1

*Use only well measurable by COT



$$30 < p_T^{\ell} < 55\ \mathrm{GeV}$$

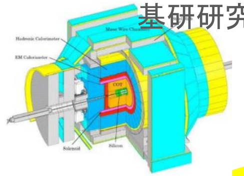
$$30 < p_T^{\nu} < 55\ \mathrm{GeV}$$

e: $|\eta| < 2.4$ (exclude $1.2 < |\eta| < 1.82$)

μ: $|\eta| < 2.4$ ID+MS で同定=> ID だけで運動量

$$p_T^{\ell} > 30\ \mathrm{GeV}$$

$$p_T^{\mathrm{miss}} > 30\ \mathrm{GeV}$$

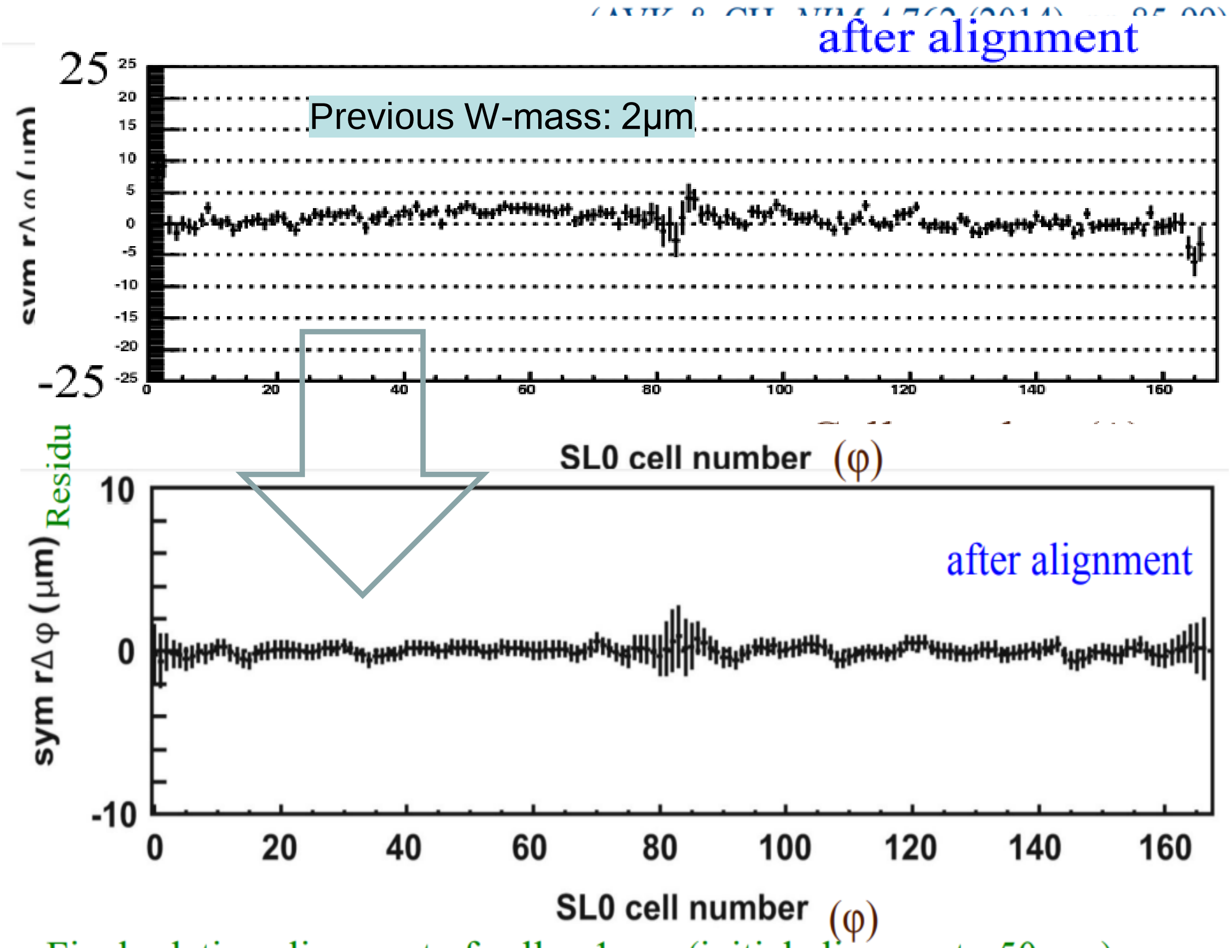


New in 2022 analysis

1-1 CDF COT alignment

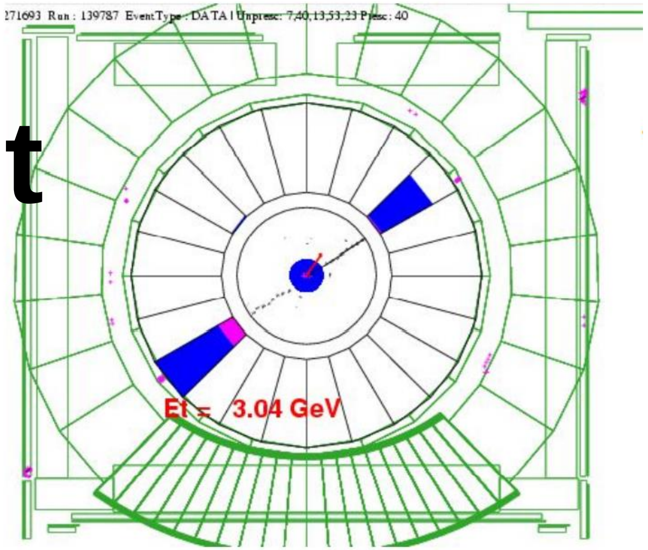
480k cosmic muons

Residuals of COT cells after alignment



Final relative alignment of cells ~1 μm (initial alignment ~50 μm)

Previous W-mass(2012): 2-5μm

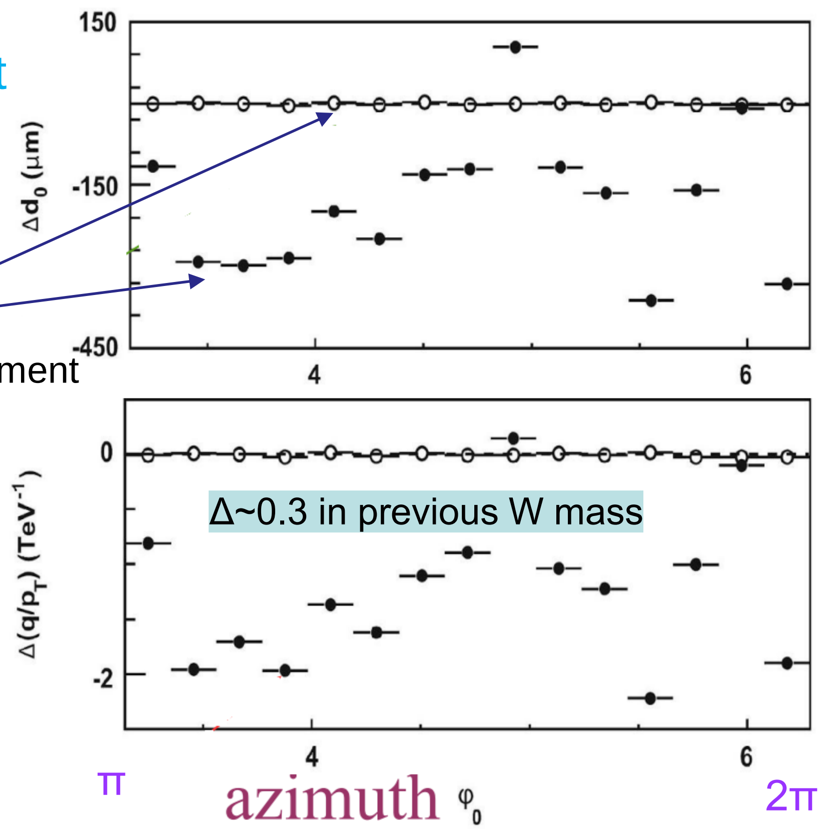


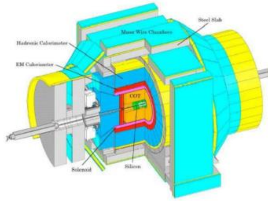
COT 領域を通過する宇宙線
⇒同一pの円弧

Impact point resolution

Curvature resolution

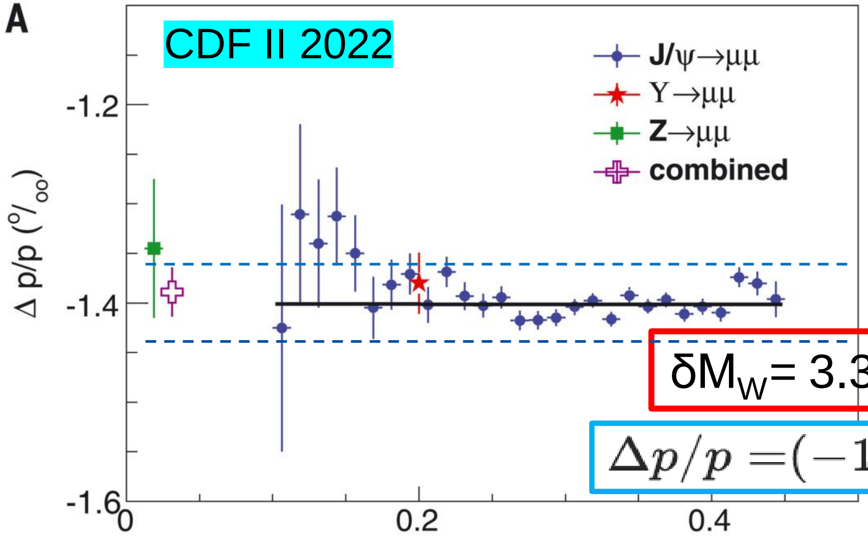
BC momentumへの影響





Muon momentum scale

✓ **Use J/ψ, Y for scale calibration**

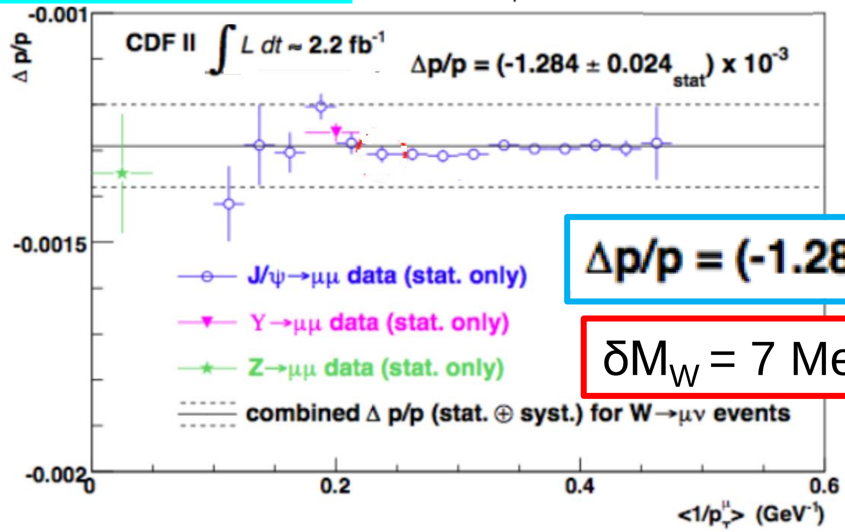


< GeV / p_T^μ >

δM_W= 3.3 MeV inc. syst.

$\Delta p/p = (-1393 \pm 26)$ ppm

previous CDF II 2012



$\Delta p/p = (-1.284 \pm 0.024_{stat}) \times 10^{-3}$

δM_W = 7 MeV inc. syst.

M_W:+ 8.8MeV by new calibration

✓ **Use Z mass for scale calibration**

統計量で精度が制限.

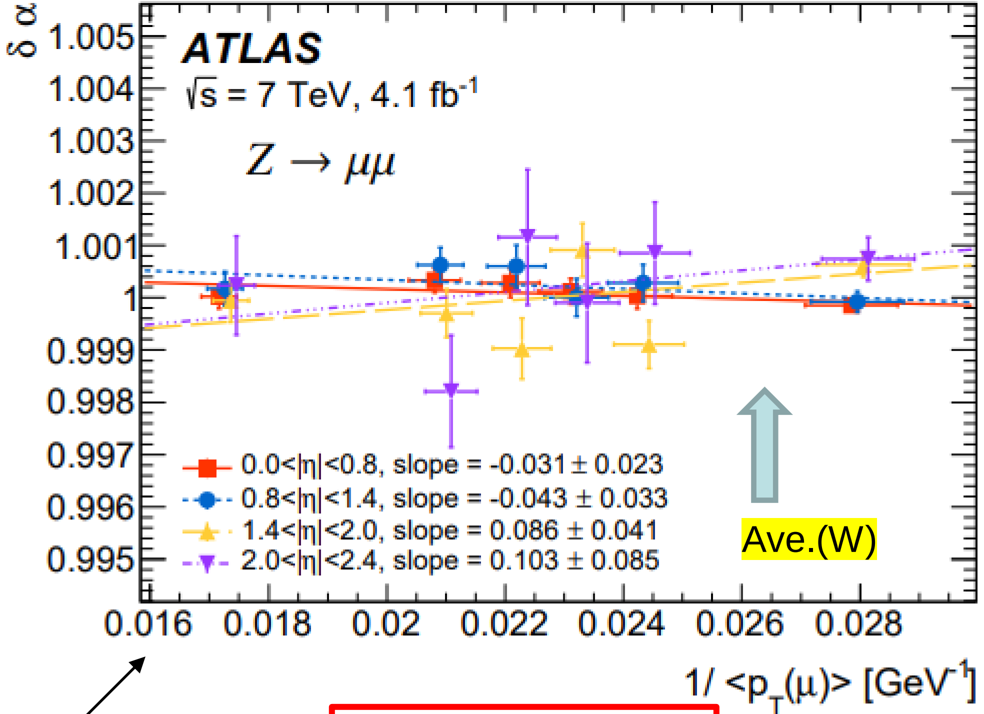
20－50ppm in |η|<2

400-700ppm in |η|>2

決定前は？

$\frac{m(J/\psi)\_data}{m(J/\psi)\_SM}$ =-1.2‰

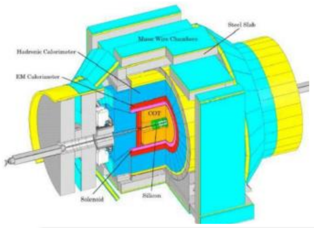
運動量スケールはη領域毎にZで決定済み



Ave.(W)

2つのミュー粒子の平均運動量の逆数

δM_W = 9.7 MeV



Momentum scale systematics

Source	J/ψ		Υ		Correlation
QED	1		1		100 %
Magnetic field non-uniformity	13		13	B-filed	100
Ionizing material correction	11		8	material	100
Resolution model	10		1		100
Background model	7		6		0
COT alignment correction	4		8		0
Trigger efficiency	18		9	Low pT modeling	100
Fit range	2		1		100
$\Delta p/p$ step size	2		2		0
World-average mass value	4		27		0
Total systematic	29	ppm	34	ppm	16 ppm
Statistical NBC (BC)	2		13(10)		0
Total	29	ppm	36	ppm	16 ppm

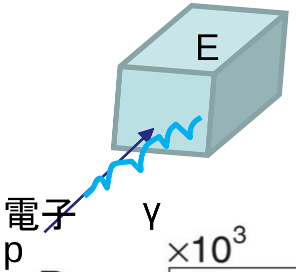
was (2012 paper)
ΔM= 7 MeV

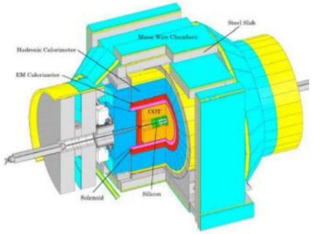
$\Delta M_{W,Z}$= 3.3 MeV

$\|\eta_\ell\|$ range	[0.0, 0.8]		[0.8, 1.4] [1.4, 2.0] [2.0, 2.4] Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]				
Momentum scale	8.9	9.3	8.4	8.8
Momentum resolution	1.8	2.0	1.0	1.2
Sagitta bias	0.7	0.8	0.6	0.6
Reconstruction and isolation efficiencies	4.0	3.6	2.7	2.2
Trigger efficiency	5.6	5.0	4.1	3.2
Total	11.4	11.4	9.8	9.7

δM_W = 9.7 MeV

1-3 CDF Electron energy calibration(1/2)

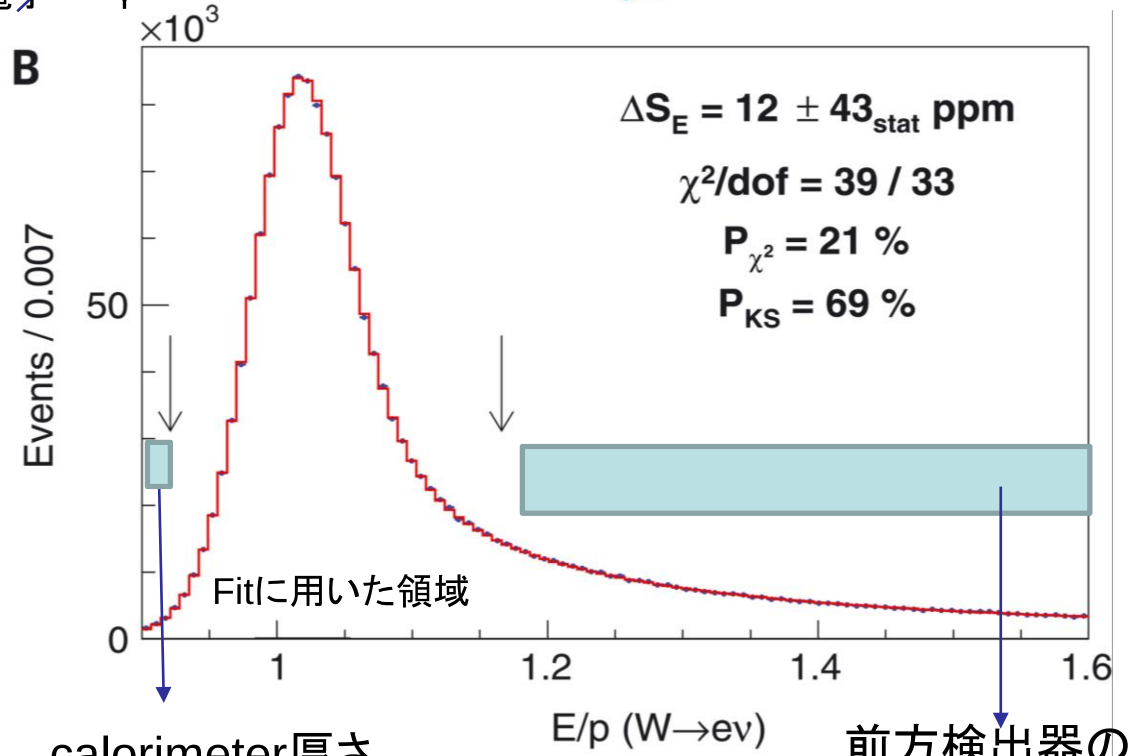


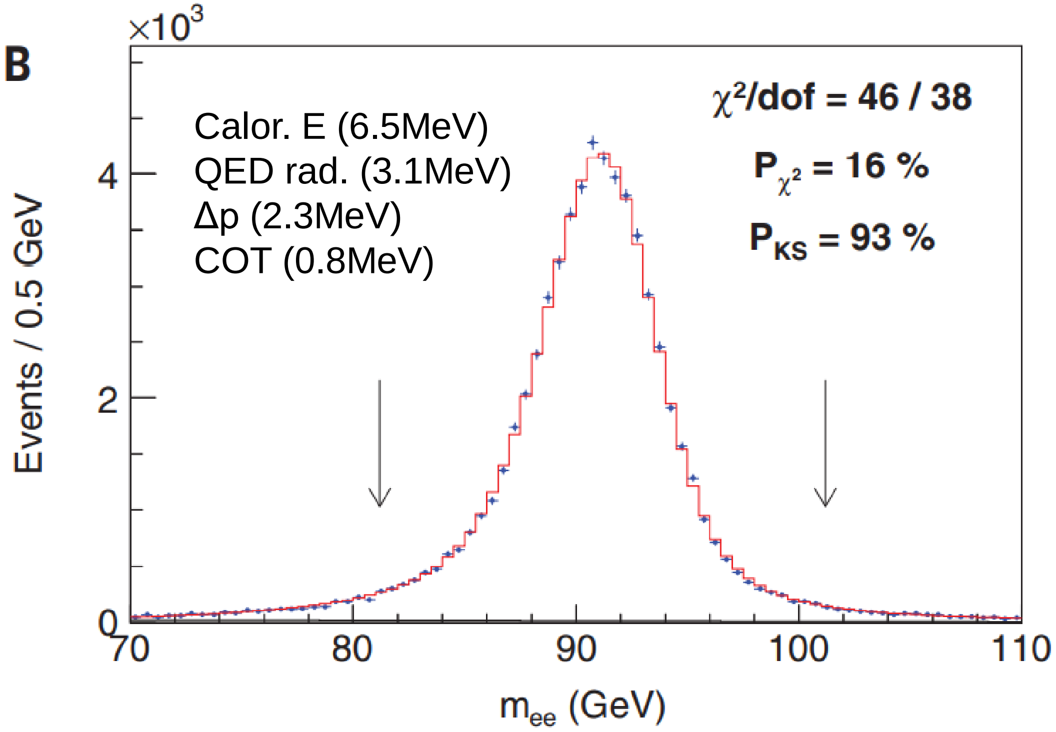


Cross-check on Z-pole

(analysis unblinded after E/p study completed)

$M_Z=91194.3\pm13.8_{stat}\pm6.5_{calorimeter}\pm2.3_{momentum}\pm3.1_{QED}\pm0.8_{alignment}$ MeV





calorimeter厚さの校正

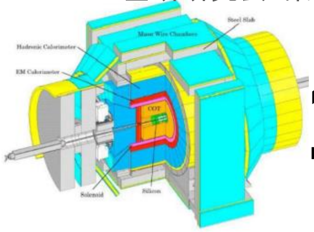
前方検出器の物質量(radiation)の校正

補正値 $S_{X0} = 1.049 \pm 0.002$

Consistent with PDG: 91188 MeV

ΔM_W= 0.4 MeV

ΔM_W= 2.7 MeV

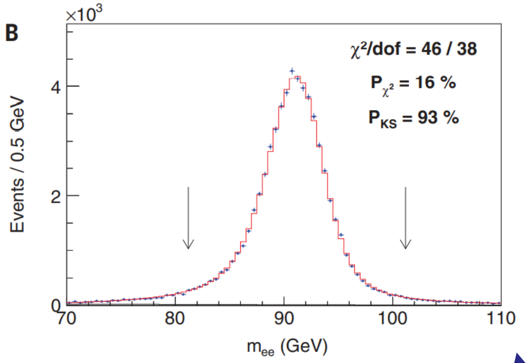


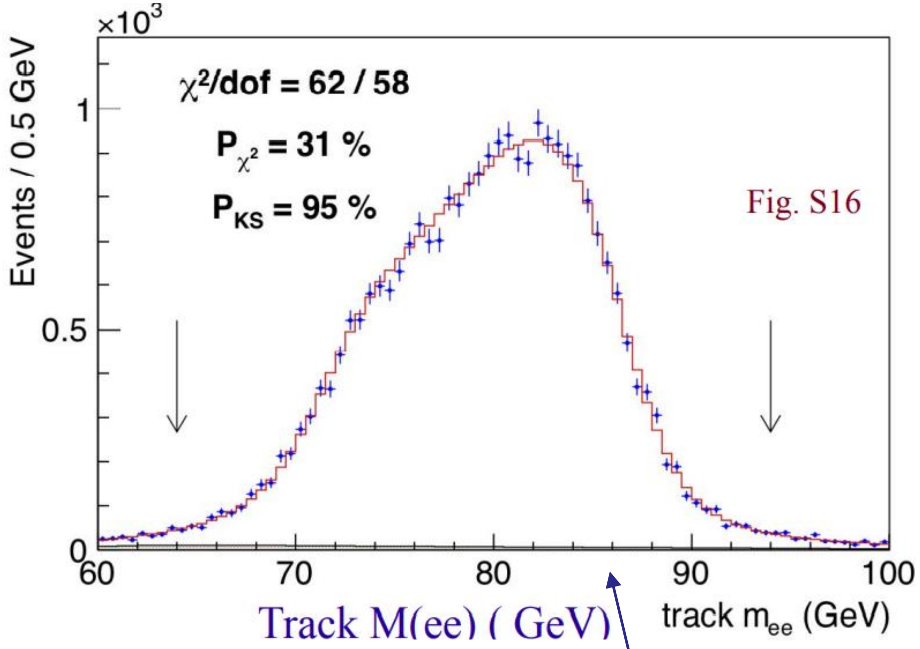
1-3 Electron energy calibration (2/2)

Track only M_Z(ee): blinded measurement

M(ee) using Calorimeter
M(ee) using Track
は矛盾なく一致

E/p の領域毎の質量値も矛盾ない
⇒ E/p modelingが妥当





Electrons	Calorimeter	Track
$E/p < 1.1$ only	$91\,190.9 \pm 19.7$	$91\,215.2 \pm 22.4$
$E/p > 1.1$ and $E/p < 1.1$	$91\,201.1 \pm 21.5$	$91\,259.9 \pm 39.0$
$E/p > 1.1$ only	$91\,184.5 \pm 46.4$	$91\,167.7 \pm 109.9$

More radiative

Calorimeter scale factor(E/p+Z calibration) =-14±72 ppm

ΔM_W= 5.8 MeV

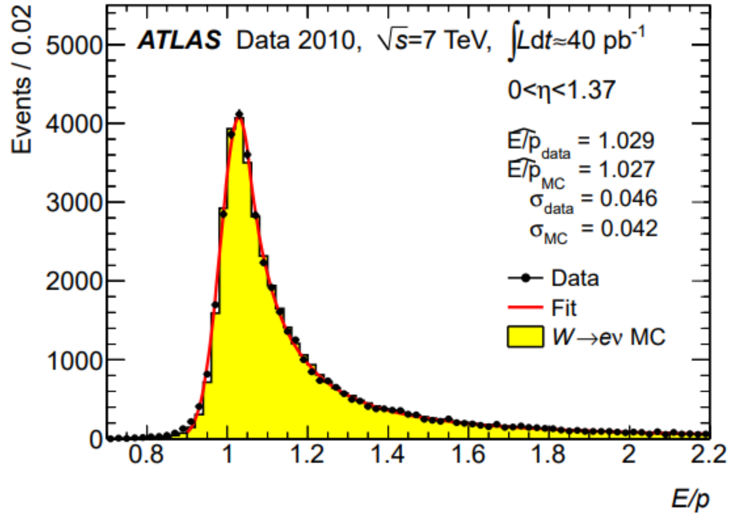
Electron energy scale : ATLAS

- E/p calibrations using Z→ee

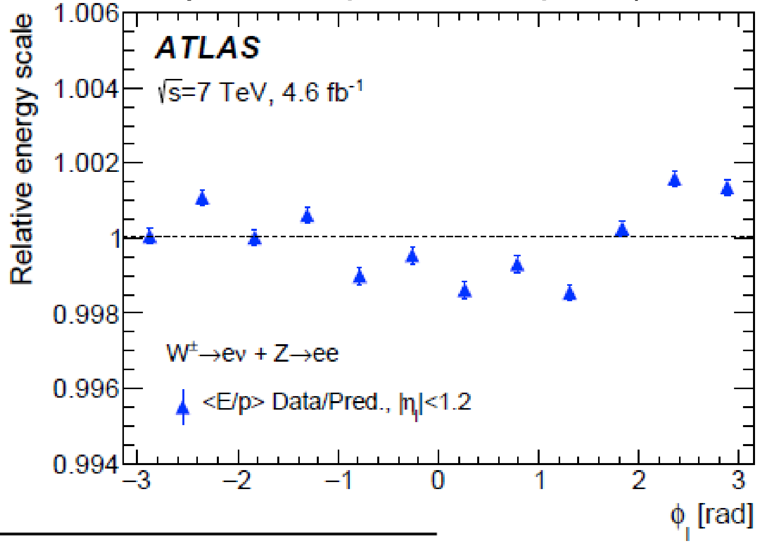
不定性 = 94 ppm (η で平均)

CDF:72ppm

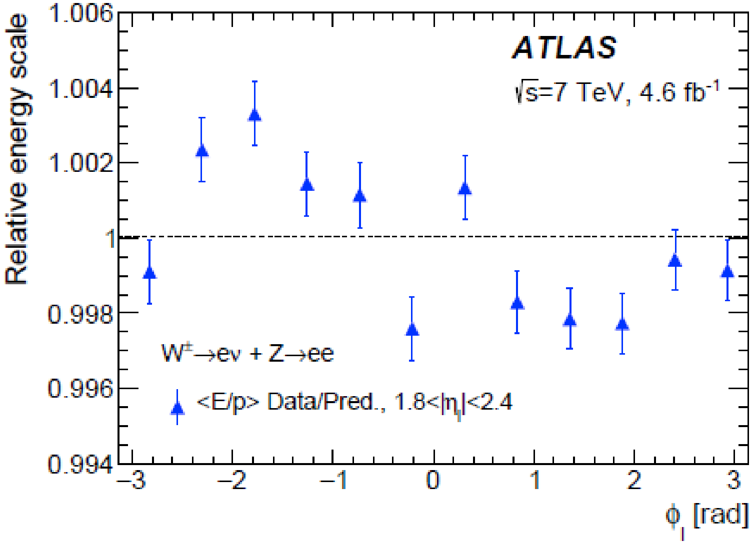
E/p分布(WのデータとMC)



E/p校正のφ依存性 (η<1.2)



E/p校正のφ依存性 (1.8<η<2.4)



$\|\eta_\ell\|$ range	[0.0, 0.6]		[0.6, 1.2]		[1.82, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]								
Energy scale	10.4	10.3	10.8	10.1	16.1	17.1	8.1	8.0
Energy resolution	5.0	6.0	7.3	6.7	10.4	15.5	3.5	5.5
Energy linearity	2.2	4.2	5.8	8.9	8.6	10.6	3.4	5.5
Energy tails	2.3	3.3	2.3	3.3	2.3	3.3	2.3	3.3
Reconstruction efficiency	10.5	8.8	9.9	7.8	14.5	11.0	7.2	6.0
Identification efficiency	10.4	7.7	11.7	8.8	16.7	12.1	7.3	5.6
Trigger and isolation efficiencies	0.2	0.5	0.3	0.5	2.0	2.2	0.8	0.9
Charge mismeasurement	0.2	0.2	0.2	0.2	1.5	1.5	0.1	0.1
Total	19.0	17.5	21.1	19.4	30.7	30.5	14.2	14.3

W/Z difference⇒ p_T difference:
←セル間校正、直線性校正、ペデスタル
30-120 ppm depending on η : 54 ppm in ave.

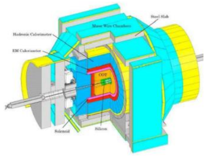
総合して、

Energy scale ⇒ 8.1/8.0 MeV on m_W

Reconstruction/Id efficiencies も寄与が大きい
⇒ 6-7 MeV each

ΔM_W= 14.2 MeV

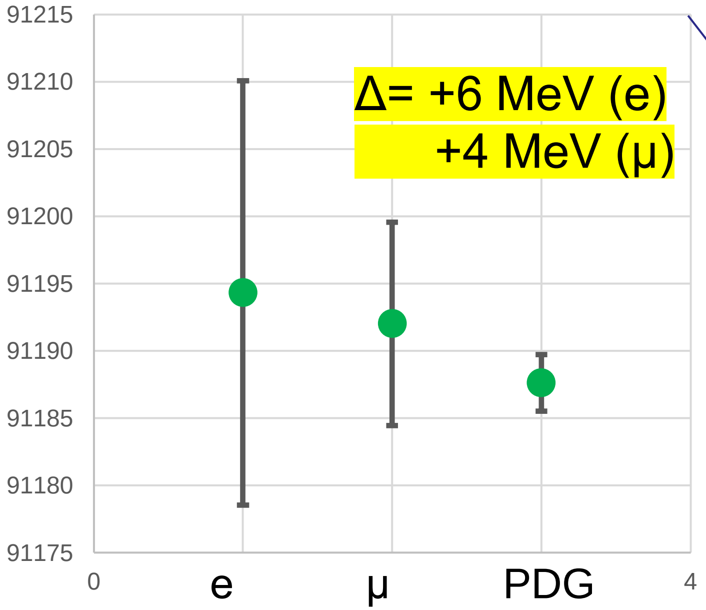
CDF:5.8MeV



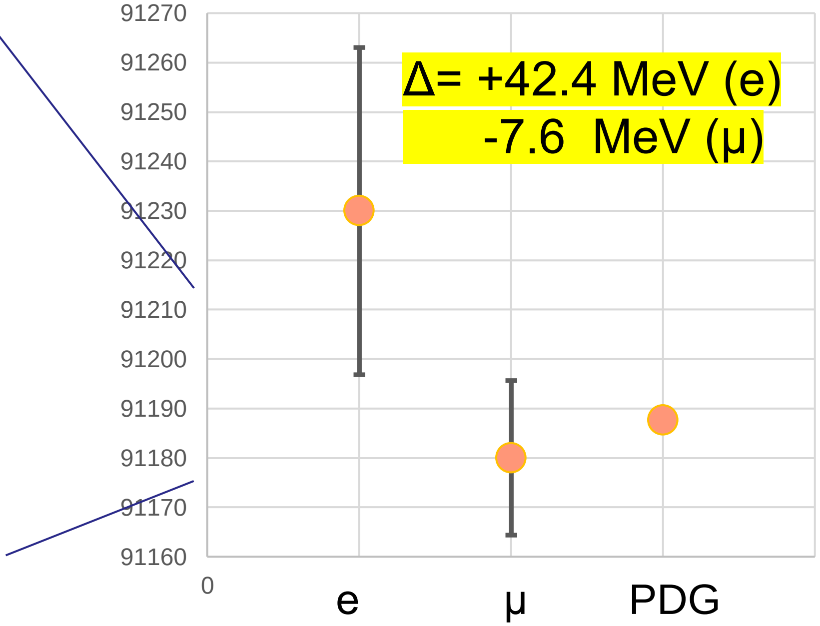
M_Z validation (CDF/CDF-II – ATLAS)

PDG $91{,}187.6 \pm 2.1$ MeV

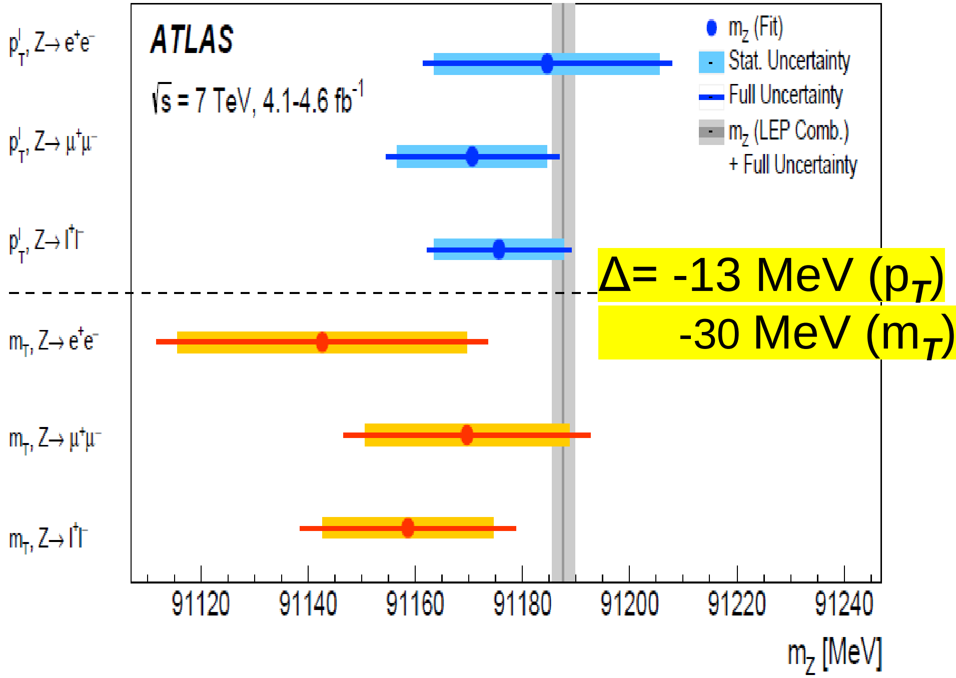
Science (2022 CDF-II)



(2012 CDF-II)

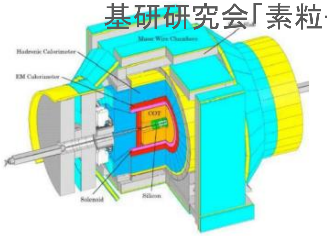


ATLAS はPDG $\boldsymbol{M_Z}$ を校正に使用
⇒ reconstruct $\boldsymbol{M_Z}$ as in $\boldsymbol{M_W}$ reconstruction
QCD 不定性も含めたスケール不定性



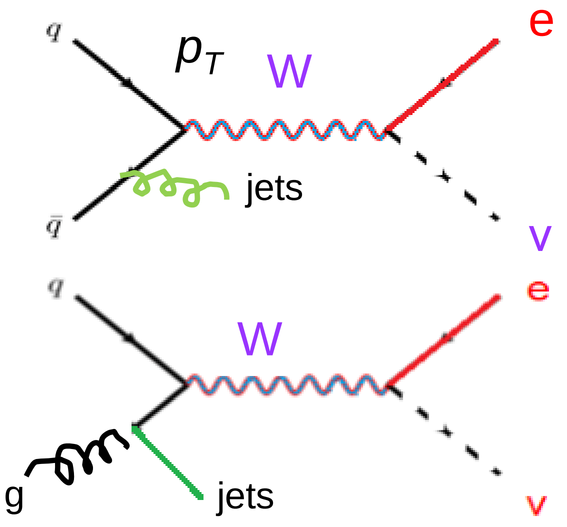
M_Z agrees PDG better in 2022 analysis
←検出器の理解が向上

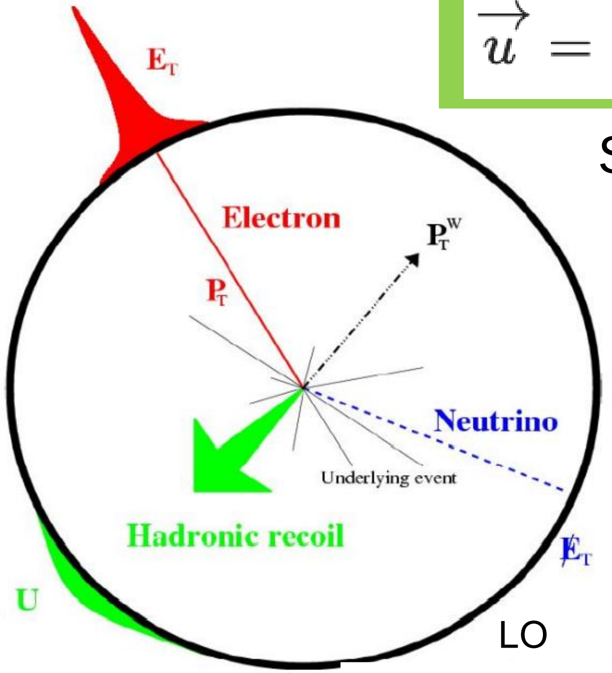
(統計的にずれはないが), 中心値は:
CDF は $\boldsymbol{M_W}$ ~5 MeV 程度高め
ATLAS は $\boldsymbol{M_W}$ ~20 MeV 程度低め



(2) QCD activities -neutrino

(0) PDF: NNPDF3.1





$$\vec{p}^{\,\ell}_{\mathrm{T}} = p\,\sin(\theta)\hat{n}$$

$$\vec{u} = \Sigma_i E_i \sin(\theta_i)\hat{n}_i$$

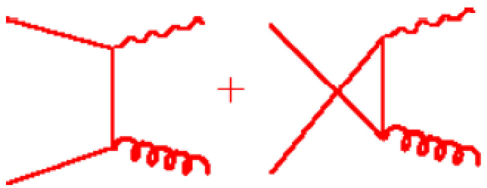
$$\vec{p}^{\,\nu}_{\mathrm{T}} \equiv -\vec{p}^{\,\ell}_{\mathrm{T}} - \vec{u}$$

uの測定には補正が必要

Simulation: RESBOS

NLO QCD + NNLL resummation

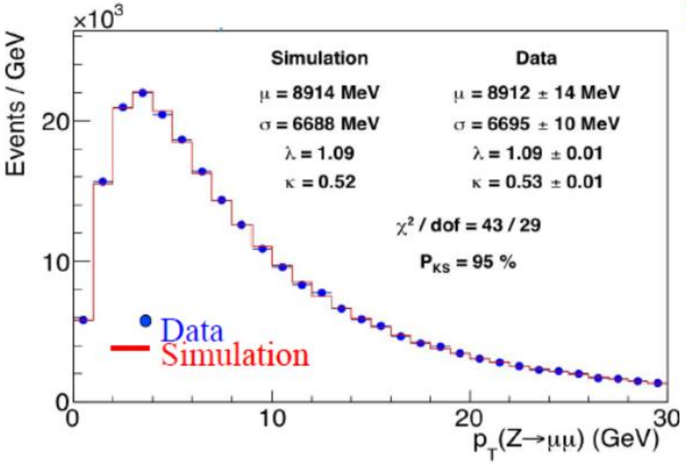
NLO perturbative



$$\alpha_s^n \log^{2n}\left(\frac{p_T^2}{M_W^2}\right)$$

as $p_T \to 0$, no longer converges

⇒ resummation required

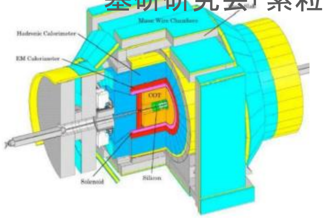


LO NLO NNLO NNNLO .....

$$\begin{aligned}\sigma = 1 &+ \alpha_s L^2 + \alpha_s^2 L^4 + \alpha_s^3 L^6 + \cdots && \text{Leading Log (LL)}\\ &+ \alpha_s L + \alpha_s^2 L^3 + \alpha_s^3 L^5 + \cdots && \text{Next to LL(NLL)}\\ &+ \alpha_s^2 L^2 + \alpha_s^3 L^4 + \cdots && \text{(NNLL)}\end{aligned}$$

RESBOSのパラメータは Z のp_T および φ(ll) 分布から解析的に求める: CDF

(LL と some leading effects を補正した数値計算 : ATLAS)

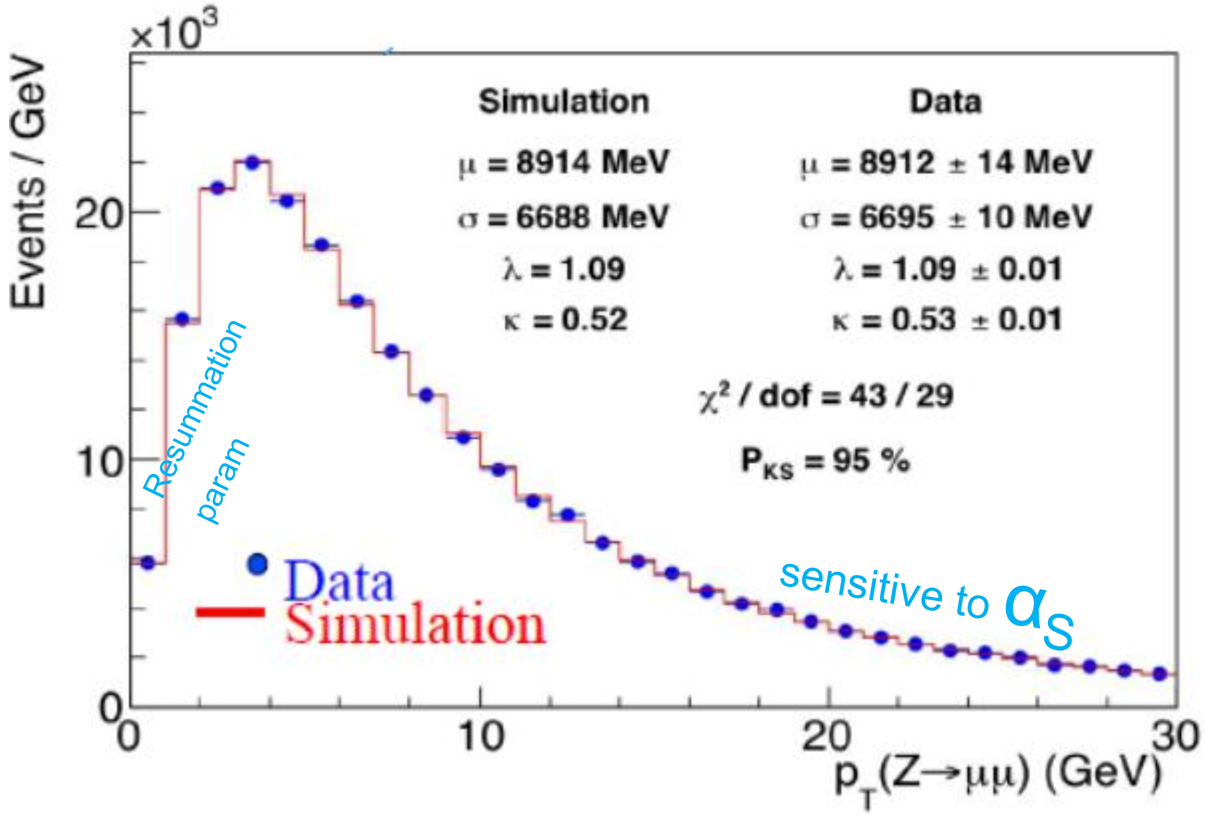


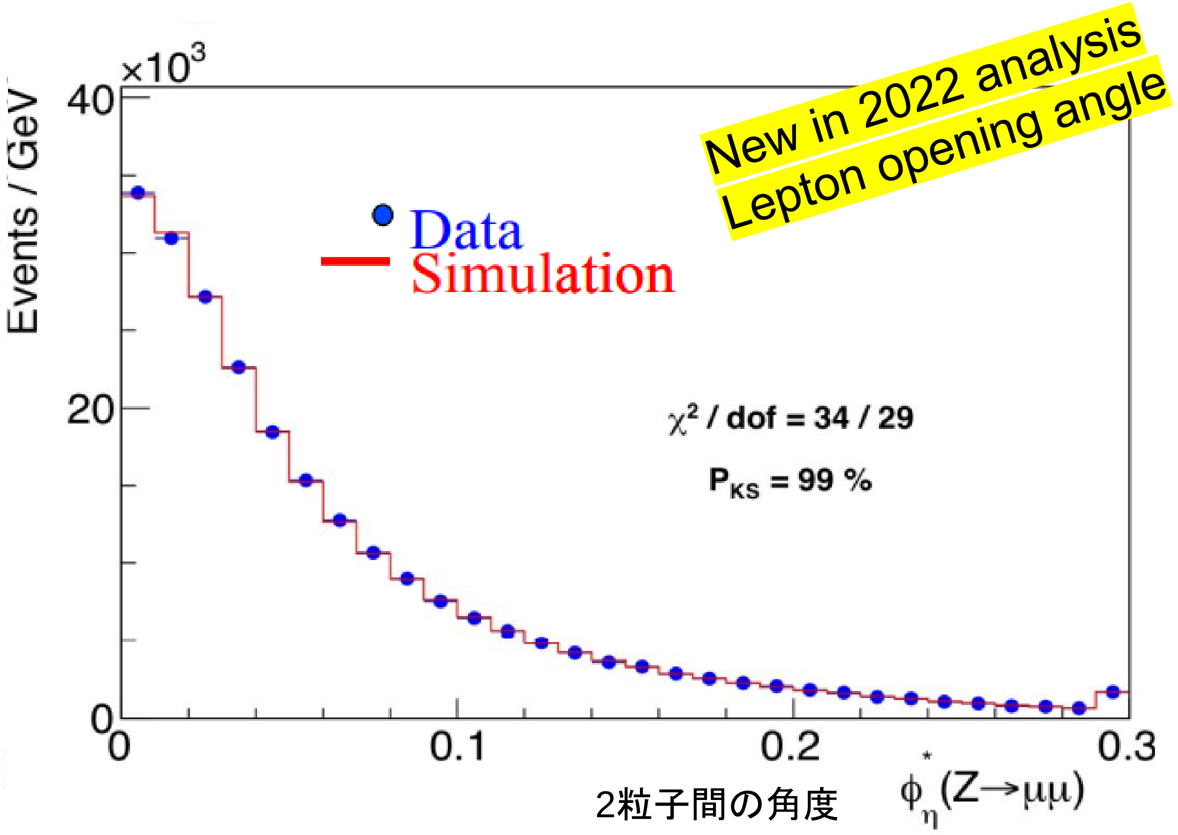
(2-1) Tune RESBOS parameters

① $Z\to\ell\ell$ events を用いた tuning

$$\left|\vec{u}\right| < 15\ \mathrm{GeV}$$

recoil の小さな事象に限定し、モデリングの精度を上げる





$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi^{\ell\ell}}{2}\right)\mathrm{sech}\left(\frac{\eta^- - \eta^+}{2}\right)$$

モデリングの不定性から $\Delta M_W = 1.8$ MeV

RESBOS tuning – detail

Brock-Landry-Nadolsky-Yuan form

低p_T spectrumの分布を規定するパラメータ

Sudakov factor

$$S = \left[g_1 - g_2 \log\left(\frac{\sqrt{\hat{s}}}{2Q_0}\right) - g_1 g_3 \log\left(\frac{100\hat{s}}{s}\right)\right] b^2$$

parton-parton energy-squared

: impact parameter between interacting partons

Q_o:=1.6GeV cutoff

proton-antiproton energy-squared

g_1,g_2,g_3: 実験データを用いて決定
(DY with fixed target/Tevatron exper.)

Global fit values

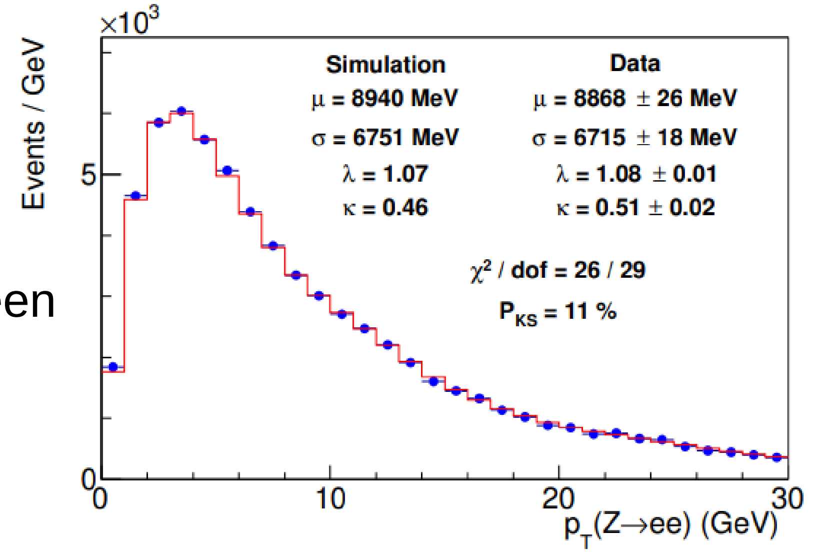
Parameter	BLNY fit
g_1	0.21
g_2	0.68
g_3	-0.60

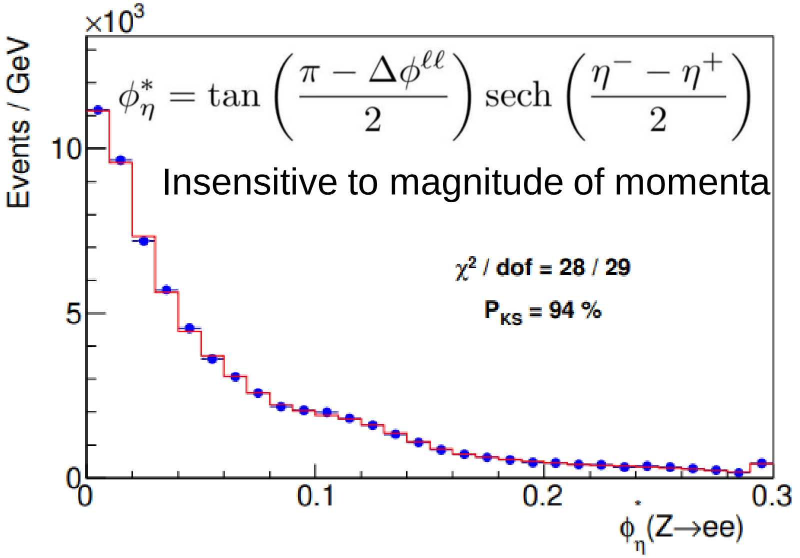
new

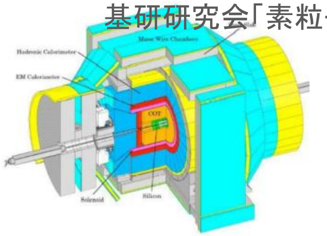
Z→*ll* p_T^Z and φ^*_η　分布から決定

p_T^W and p_T^Z 分布の違いに影響
(global fitのerror ±0.3 を含む)
+$\Delta\alpha_S$ (p_T^Z >5GeV の分布に影響する)

δM_W=0.5, 2.2, 0.5 MeV for m_T, p_T^ℓ, and p_T^ν



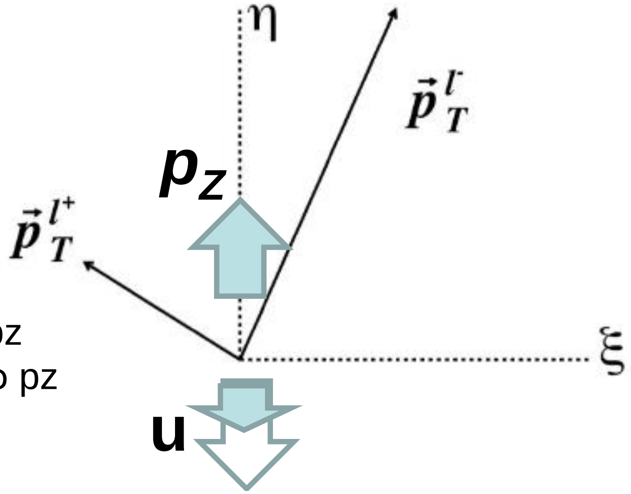




(2-1a) hadron activity verification

RESBOS parameterをtune後に,他の分布との一致を検証

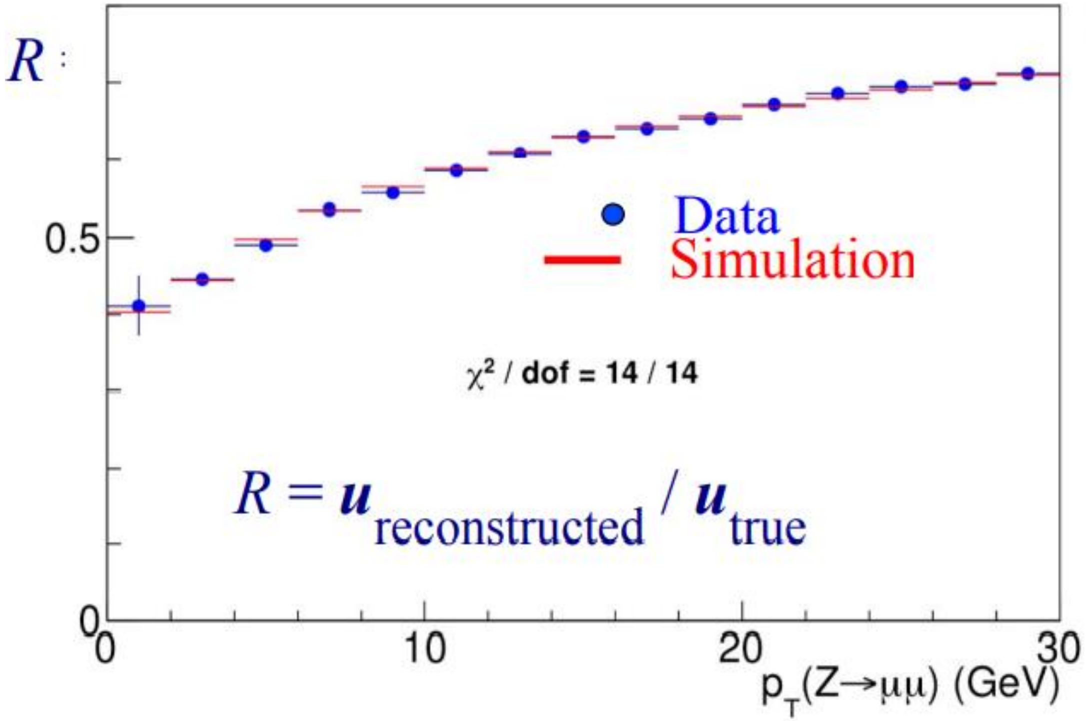
Z events

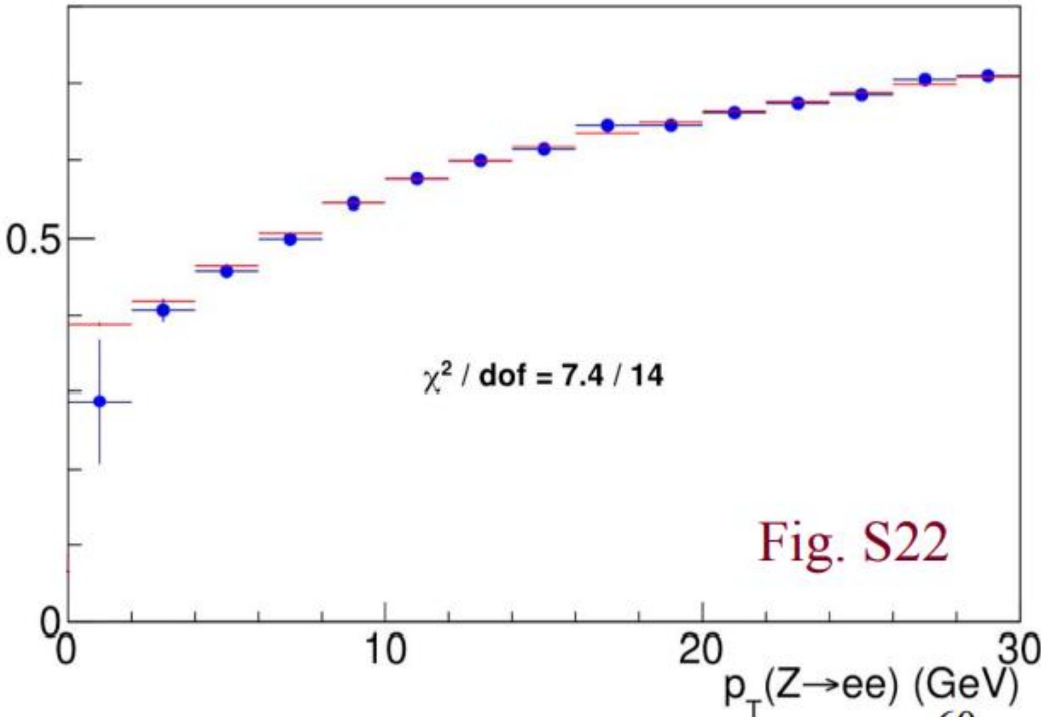


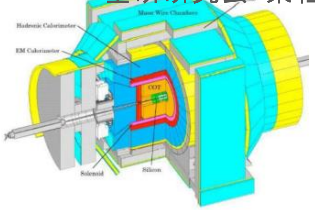
η: back to pz
ξ: parallel to pz

R: すべての recoil hadronic activity を検出できるわけではない（低エネルギーや中性成分）
⇒ Z→ℓℓ 事象で、p_T 依存性として ratioを評価

⇒よく再現できている



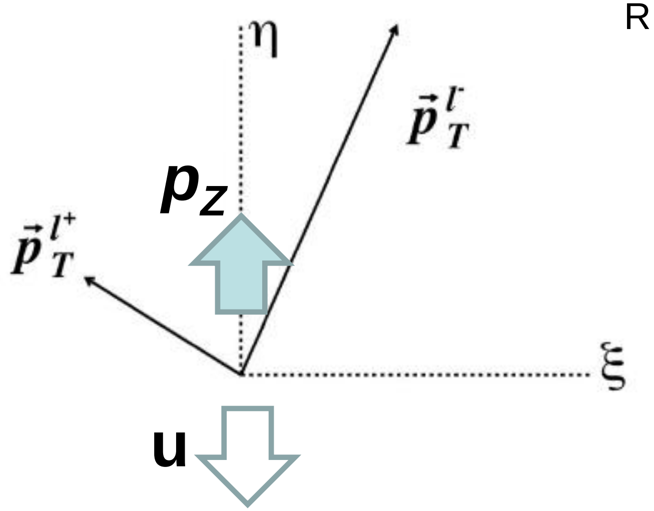




(2-1b) hadron activity verification

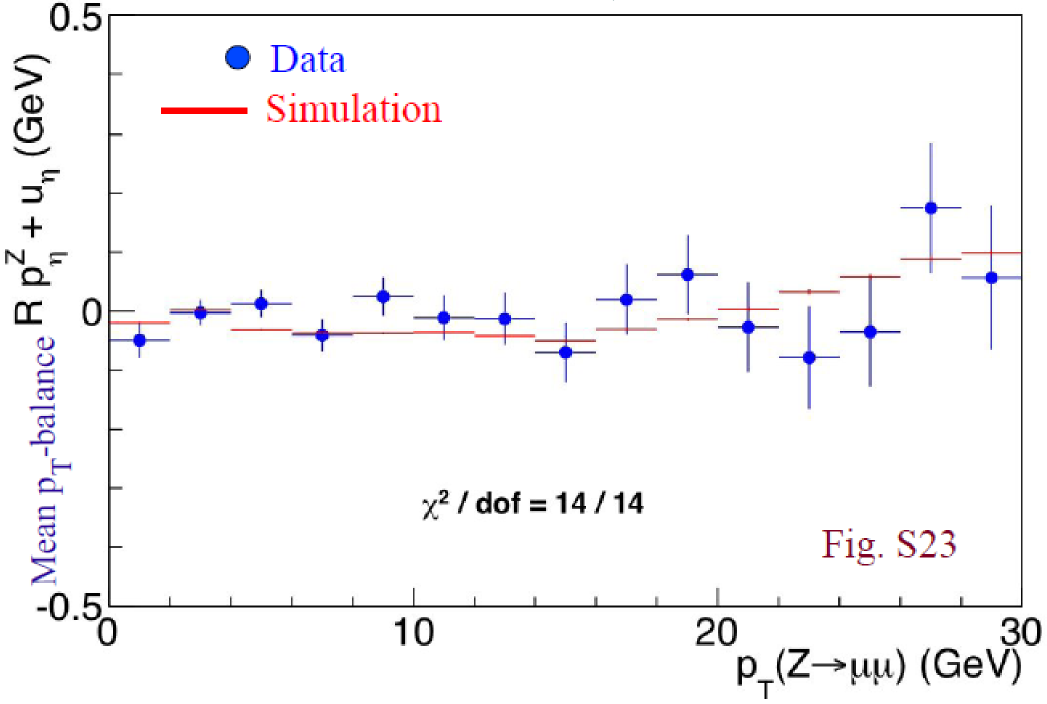
Z events

Rを加味してrecoilを評価



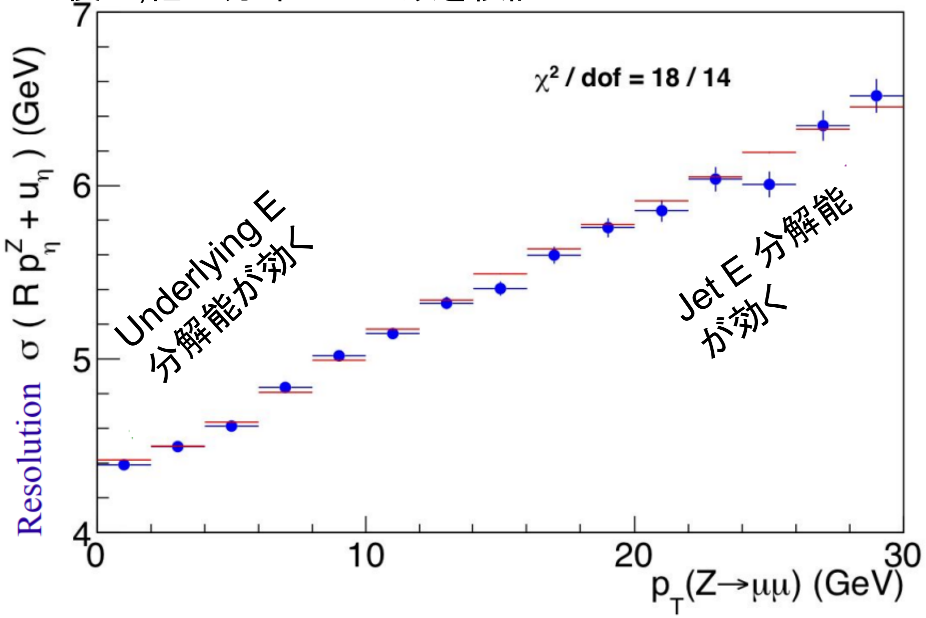
η: back to pz
ξ: parallel to pz

η方向の平均

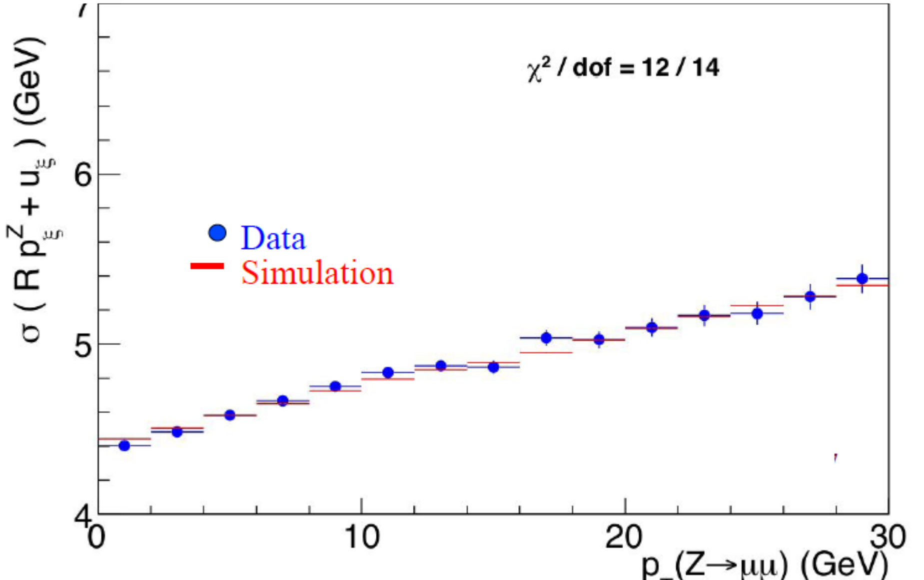


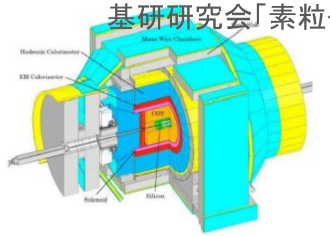
RESBOS parameterをtune後に,他の分布との一致を検証

η方向の広がり



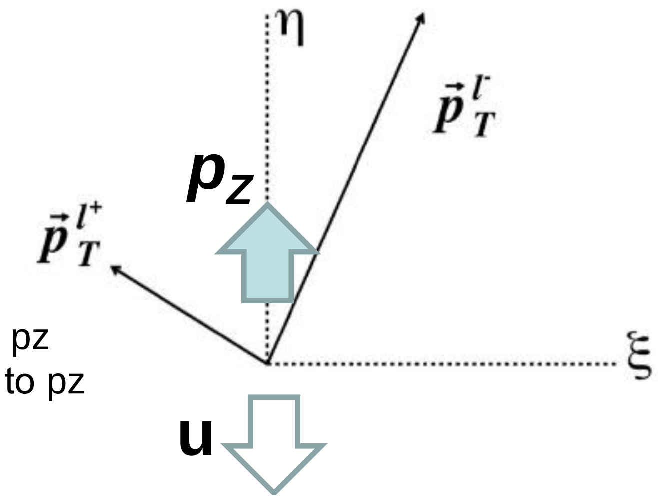
ξ方向の広がり





(2-1c) hadron activity verification

Z events

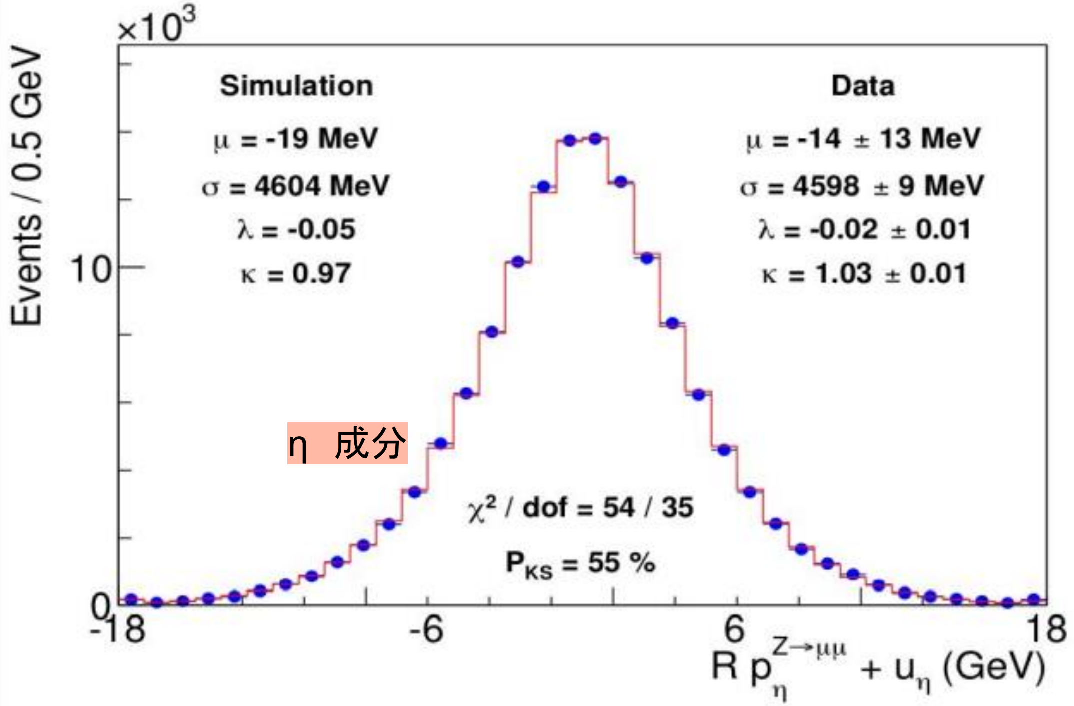


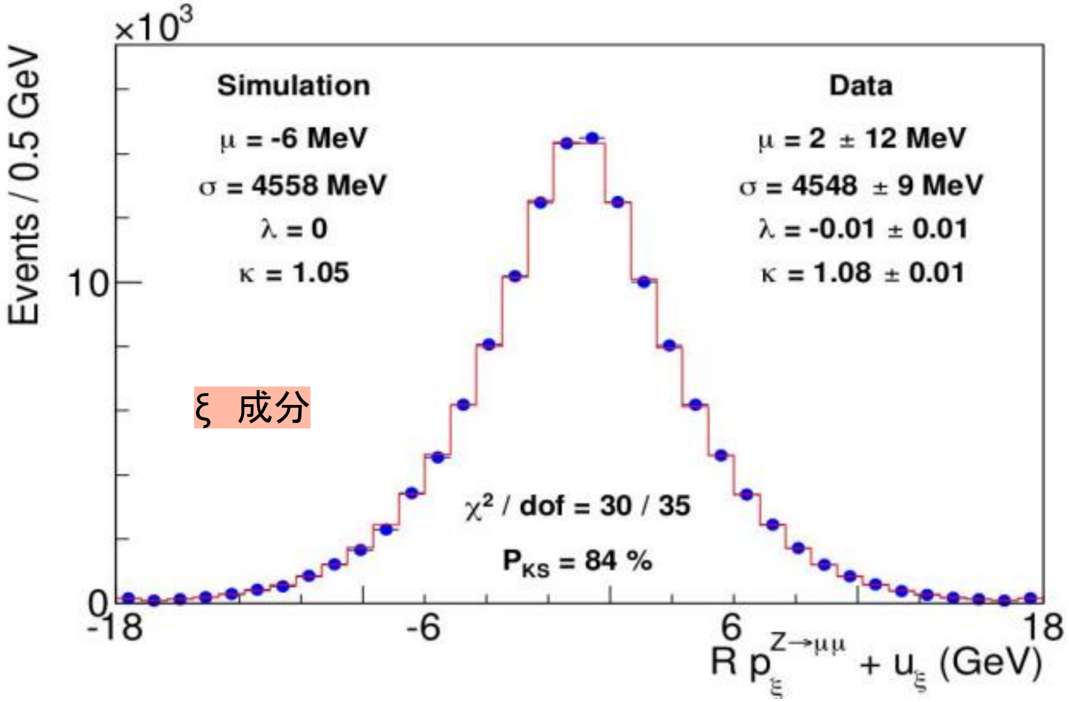
η: back to pz
ξ: parallel to pz

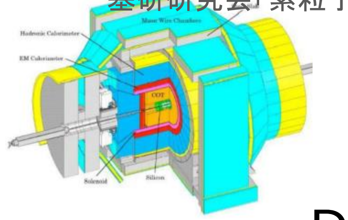
New in 2022 analysis

平均と広がり(previous page)だけでなく、高次の一致度skewness（歪度）も検証

Plots are for Z→μμ



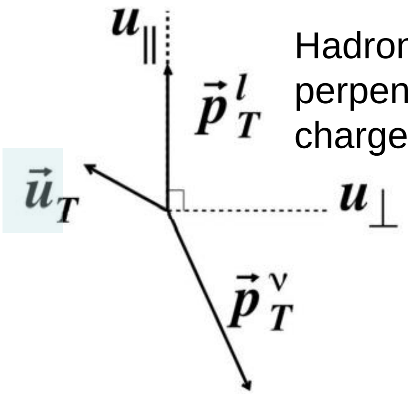




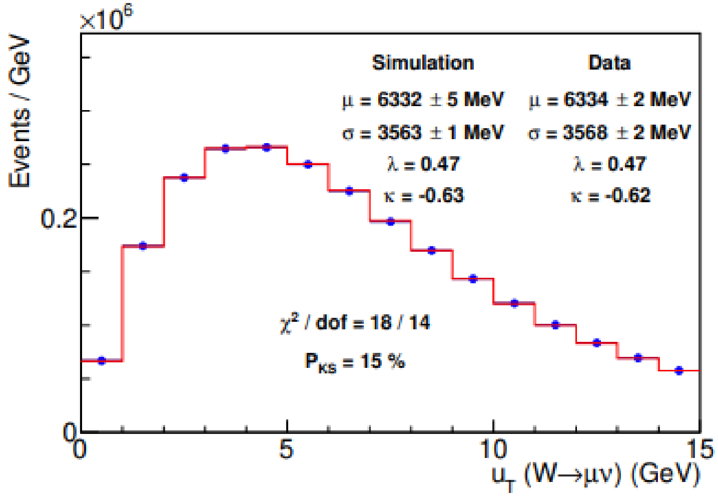
Hadronic activity in W

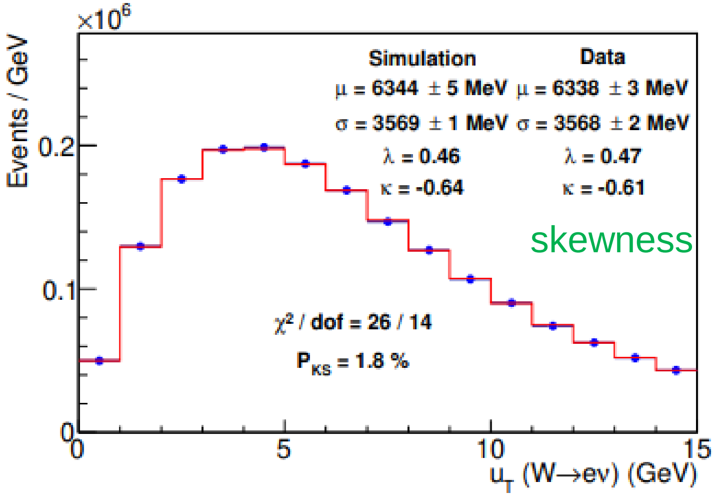
- DyqT (NNLL-QCD) で $p_T(W)/p_T(Z)$ の違いをモデル化:
  $u_T(W)$ および $u_T(Z)$分布でパラメータを決める

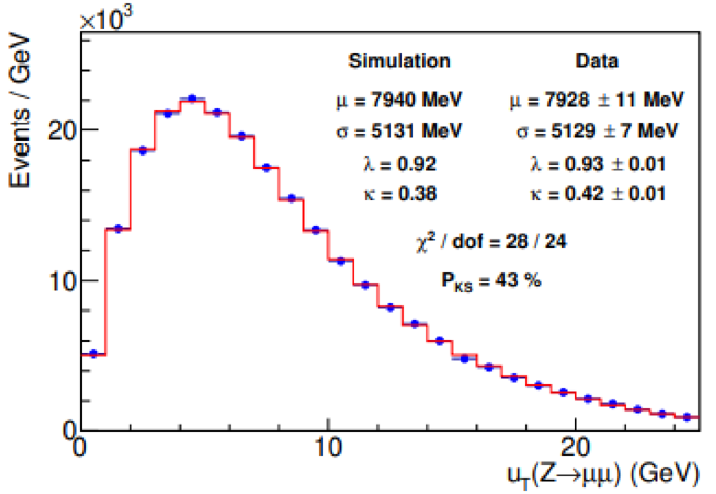
New in 2022 analysis

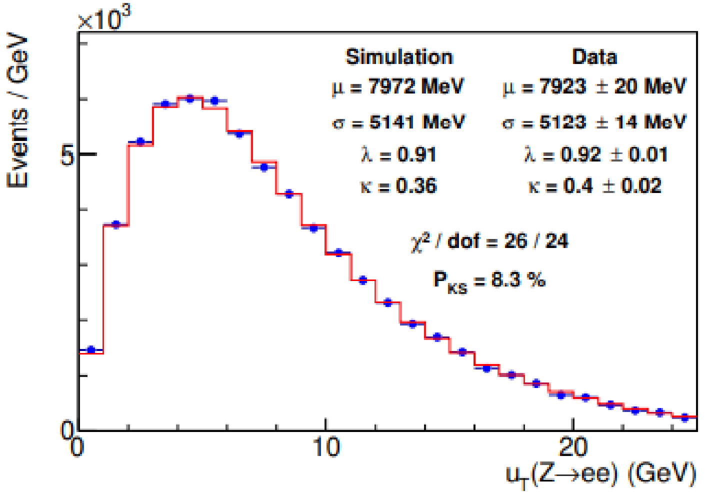


Hadronic activity perpendicular to charged lepton









この方法により m_T, p_T^ℓ, and p_T^ν での不定性を

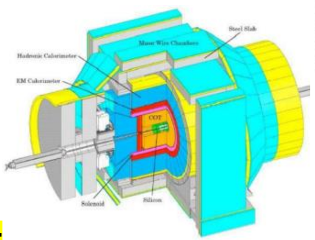
δM_W=0.8, 2.3, 0.9 MeV

に制限できた

従来の評価法(renorm./factor./resummation scales を適当に変化）だと同じく不定性は大きい

δM_W=3.5, 10.1, 3.9 MeV

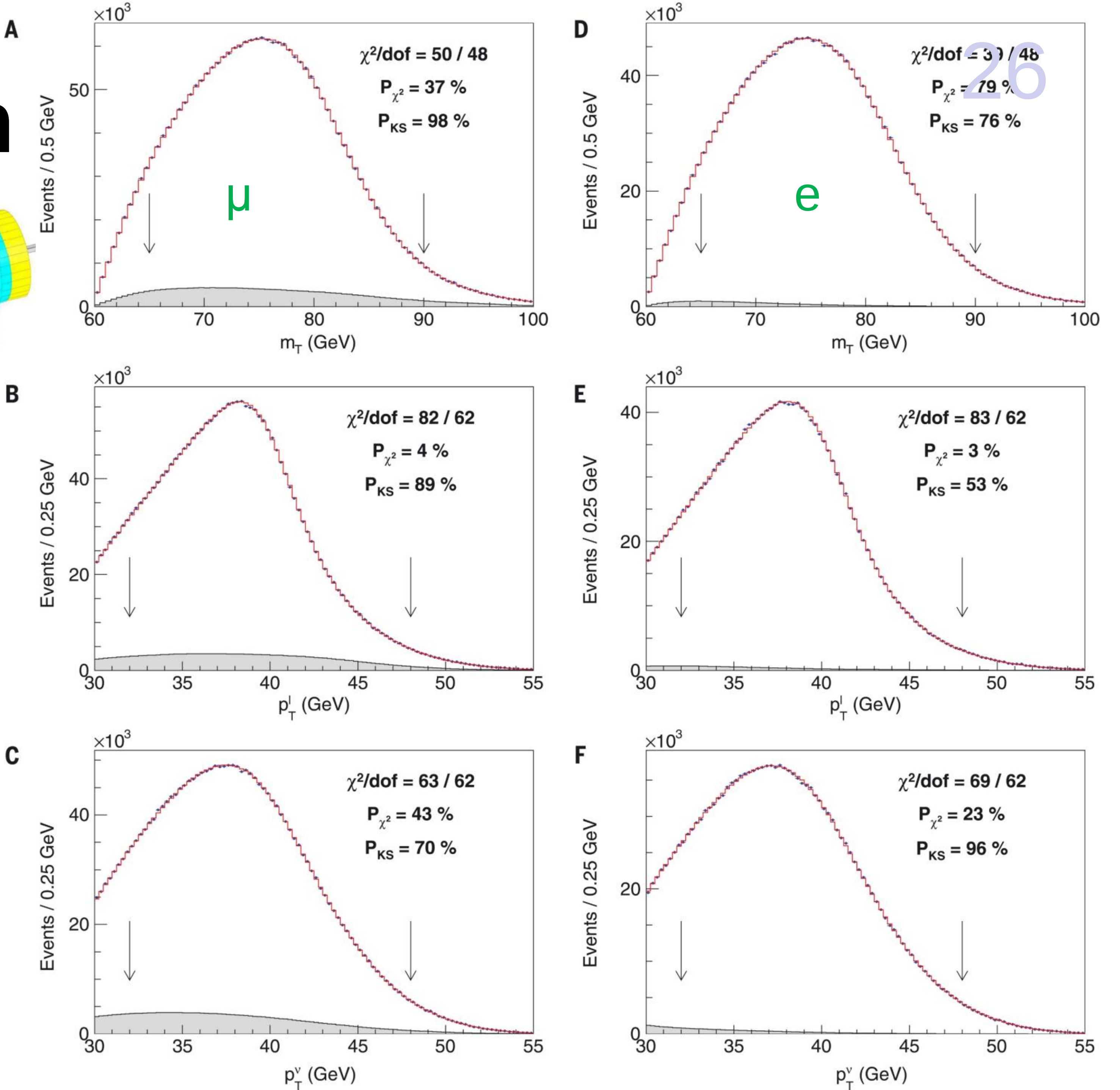
W mass extraction

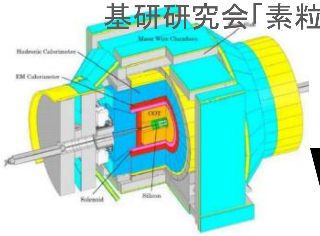


質量フィット領域は W mass 2012と
同じで最も質量不確かさが小さな領域

バックグラウンド (斜線部) の割合

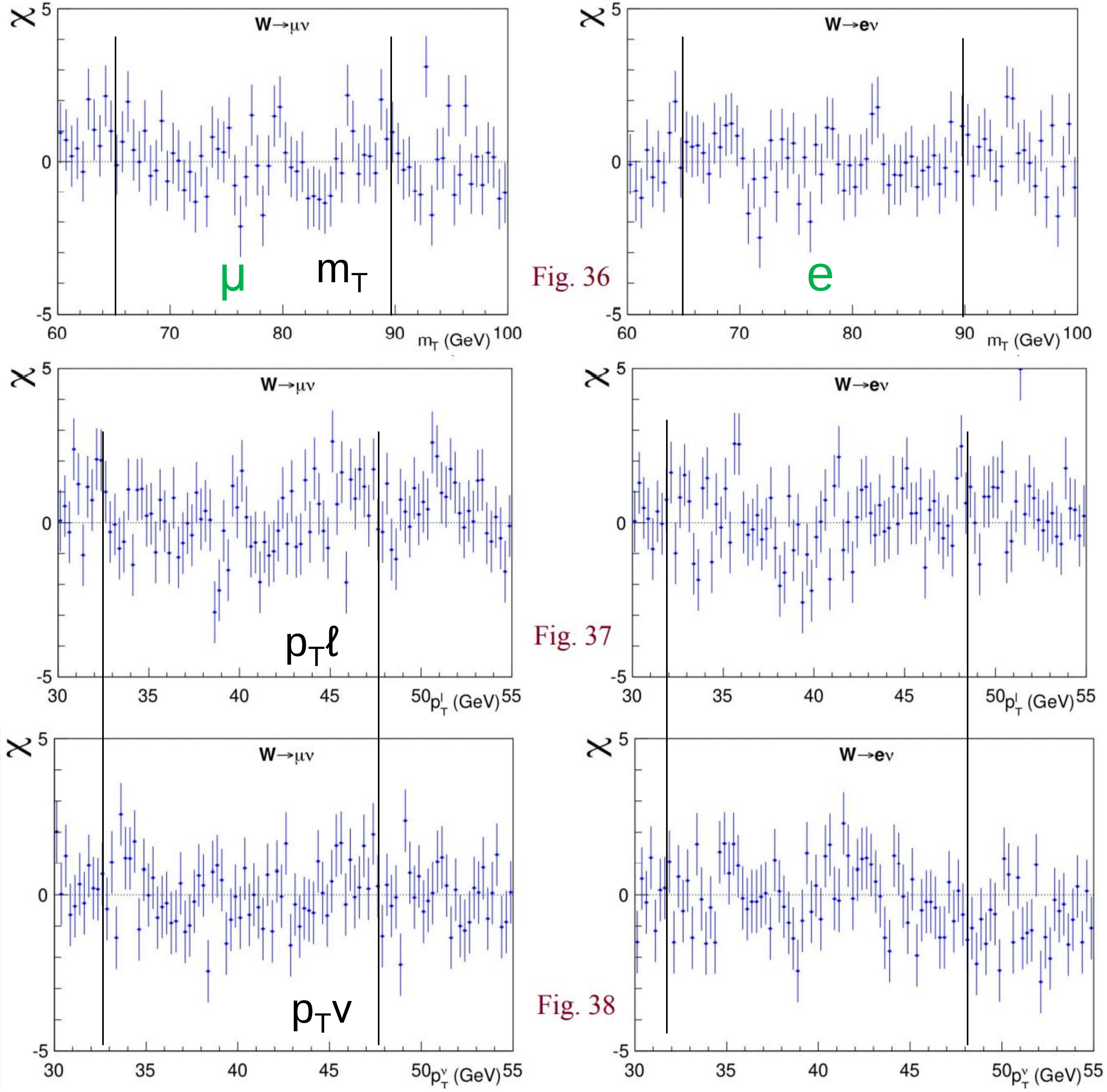
	μ	(e)
$Z \to \ell\ell$ decays (One ℓ escape)	7.37%	(0.14%)
$W \to \tau\nu$ decays ($W \to \tau\nu \to \ell\nu\bar{\nu}\nu$)	0.88%	(0.94%)
jets (Miss-identify jet as ℓ)	0.01%	(0.34%)
K decay-in-flight μ	0.20%	
宇宙線muon	0.01%	





W mass extraction

Dev/error
(error bar=1)

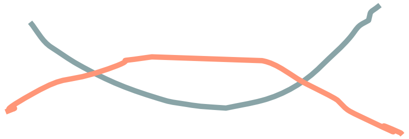


Fit residuals

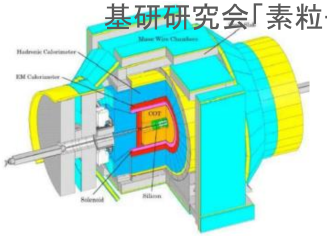
M_W 過小評価すると

M_W 過大評価すると

modelingが正しくないと



⇨ どれもなさそう

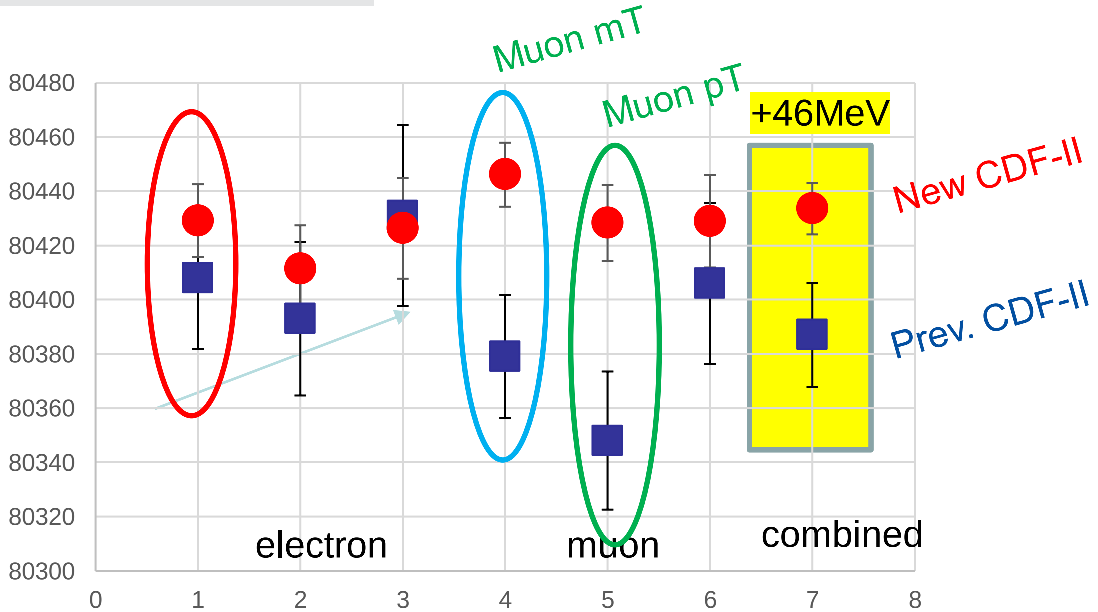


W mass: 2022 vs 2012

Distribution	W boson mass (MeV)	χ^2/dof
$m_T(e,\nu)$	$80{,}429.1 \pm 10.3_{stat} \pm 8.5_{syst}$	39/48
$p_T^{\ell}(e)$	$80{,}411.4 \pm 10.7_{stat} \pm 11.8_{syst}$	83/62
$p_T^{\nu}(e)$	$80{,}426.3 \pm 14.5_{stat} \pm 11.7_{syst}$	69/62
$m_T(\mu,\nu)$	$80{,}446.1 \pm 9.2_{stat} \pm 7.3_{syst}$	50/48
$p_T^{\ell}(\mu)$	$80{,}428.2 \pm 9.6_{stat} \pm 10.3_{syst}$	82/62
$p_T^{\nu}(\mu)$	$80{,}428.9 \pm 13.1_{stat} \pm 10.9_{syst}$	63/62
Combination	$80{,}433.5 \pm 6.4_{stat} \pm 6.9_{syst}$	7.4/5

Previous CDF II publication
PRL108, 151803 (2012)

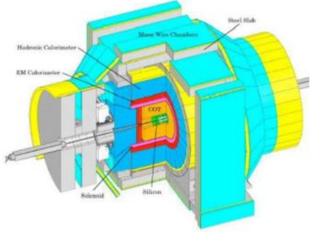
W-boson mass (MeV)
$80\,408 \pm 19_{stat.} \pm 18_{syst.}$
$80\,393 \pm 21_{stat.} \pm 19_{syst.}$
$80\,431 \pm 25_{stat.} \pm 22_{syst.}$
$80\,379 \pm 16_{stat.} \pm 16_{syst.}$
$80\,348 \pm 18_{stat.} \pm 18_{syst.}$
$80\,406 \pm 22_{stat.} \pm 20_{syst.}$
$80\,387 \pm 12_{stat} \pm 15_{syst}$



- ✓ M_W の測定値はより一様になった
- ✓ μでの測定値の増加が大きい

cf. +8.8 MeV from mom. calibration

Uncertainty vs previous CDF-II



Source		Uncertainty (MeV)
Lepton energy scale		3.0
Lepton energy resolution		1.2
Recoil energy scale		1.2
Recoil energy resolution		1.8
Lepton efficiency		0.4
Lepton removal		1.2
Backgrounds		3.3
p_T^Z model	VECBOS	1.8
p_T^W/p_T^Z model	DyqT	1.3
Parton distributions		3.9
QED radiation		2.7
W boson statistics		6.4
Total		9.4

Previous CDF II publication
PRL108, 151803 (2012)

Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal	2
Backgrounds	3
$p_T(W)$ model	5
Parton distributions	10
QED radiation	4
W-boson statistics	12
Total	19

PDF: 10⇒ 3.9 MeV
Lepton scale: 7⇒ 3.2 MeV
Recoil: 6⇒ 2.2 MeV
Total: 19⇒ 9.4 MeV

W production simulation model

(hard W/Z process) (parton shower/hadronization/underlying)

Base: NLO Powheg+Pythia8(w/AZNLO tune*)

事象ごとに以下の高次補正をする:

[mass] [rapidity] [angular coefficients] [p_T]

Breit-Wigner　　NNLO pQCD　　Parton Shower

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right]$$

BW　　Powheg+Pythia

m, p_T, *y* are of di-lepton system

(Unpolarized Xsec) × [pol effect(θ,φ)]

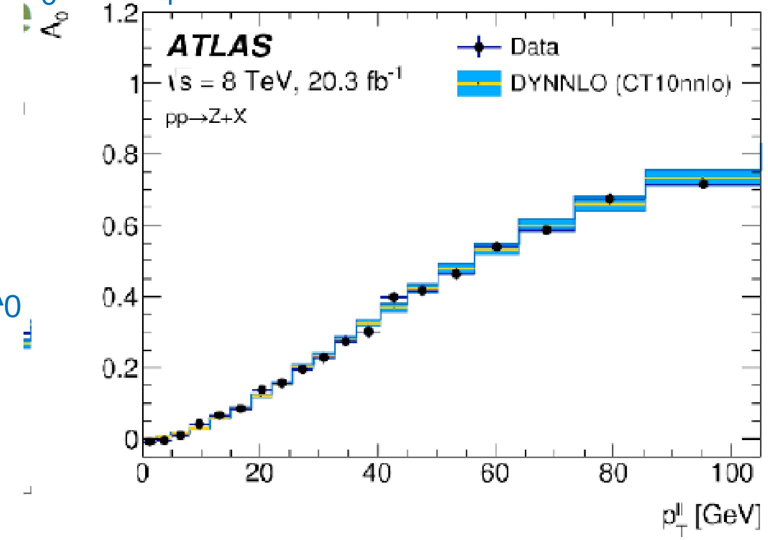
$$\frac{d\sigma}{dp_T^2\,dy\,dm\,d\cos\theta\,d\phi} = \frac{3}{16\pi}\frac{d\sigma}{dp_T^2\,dy\,dm}\times[(1+\cos^2\theta)+A_0\frac{1}{2}(1-3\cos^2\theta)$$
$$+\ A_1\sin 2\theta\cos\phi + A_2\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta$$
$$+\ A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi].$$

⇒A5以降はlow pTでは無視できる

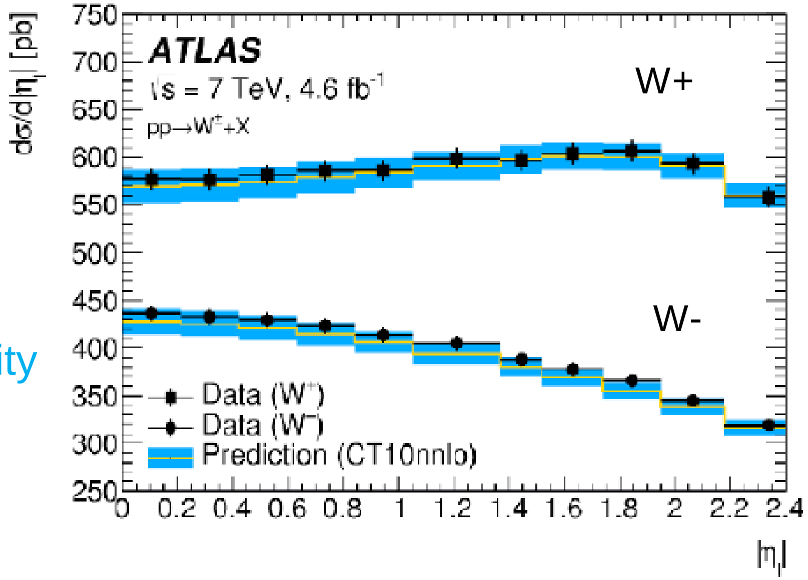
① Lepton rapidity および angular 分布

DYNNLO simulation と CT10(nnlo) PDFでモデル化:

A_0 ~ A_4 をZ eventsを用いて決定



W →leptonの pseudo-rapidity 分布で検証



① rapidity 分布の不定性 (PDF が支配的) ⇒ 8 MeV

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right]$$

Powheg+Pythia (AZ tune)

Parton shower vs. analytic resummation (CDF-II)

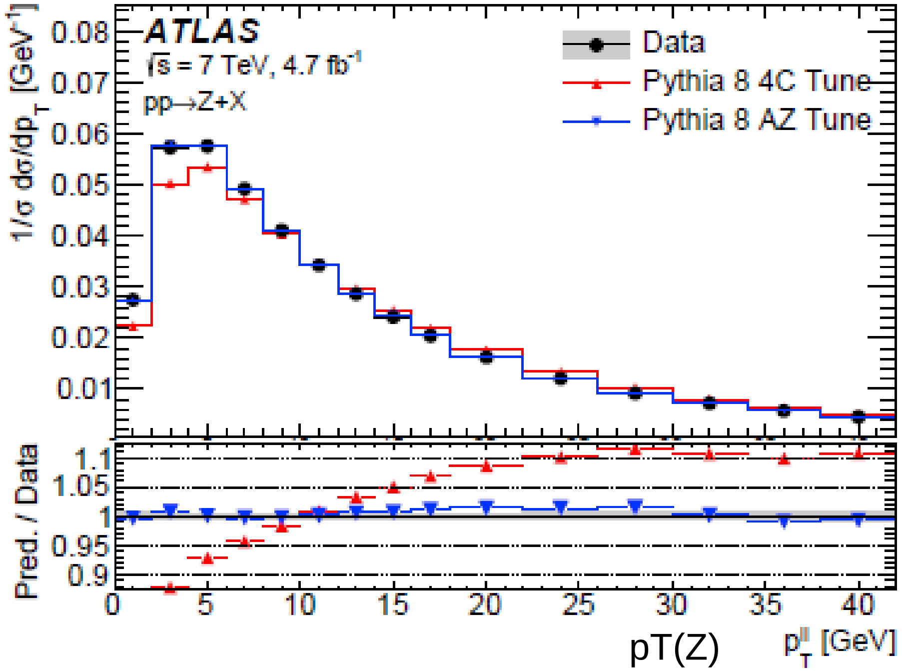
② pT distribution

Pythia8 parton shower MC (LO matrix element+reweighting for 1st parton shower ~ NLO generator+NLL resummation)

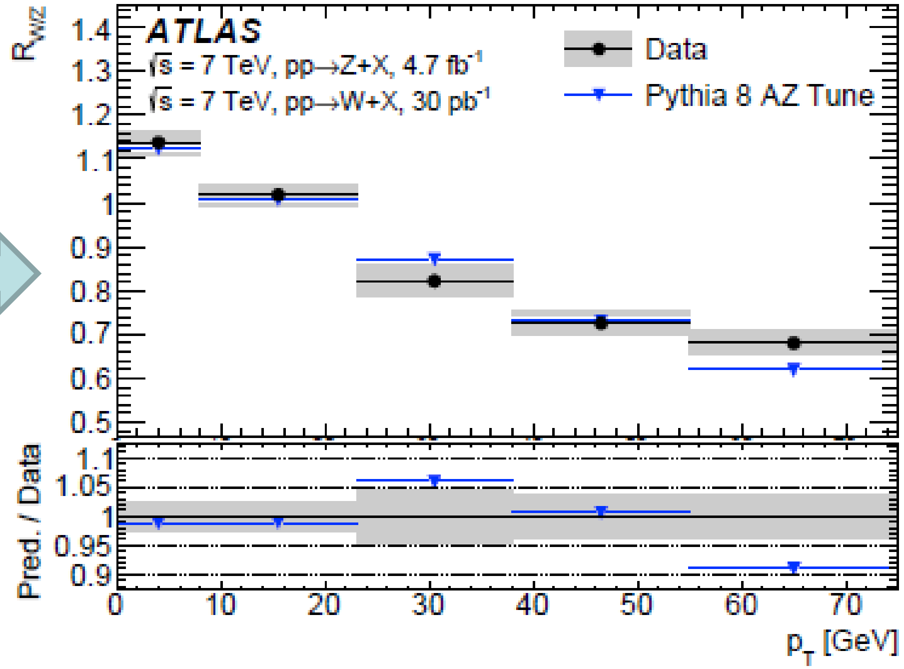
- Z pT 分布から以下のパラメータを決定: ⇒ Pythia8 AZ tune (4C: ALICE/ATLAS charged multiplicity data incorporated 2010)
  - 衝突parton のpT 分布
  - $\alpha_s(M_Z)$ を決定し QCD ISR
  - ISR infrared cutoff

4Cで合わない分を補正しAZに

$$R_{W/Z}(p_T) = \left(\frac{1}{\sigma_W}\cdot\frac{d\sigma_W(p_T)}{dp_T}\right)\left(\frac{1}{\sigma_Z}\cdot\frac{d\sigma_Z(p_T)}{dp_T}\right)^{-1}$$



pT(Z)



W/Z cross section 比を良く再現できる。特に $p_T^W < 30$ GeV.

② pT 分布の不定性 ⇒6 MeV

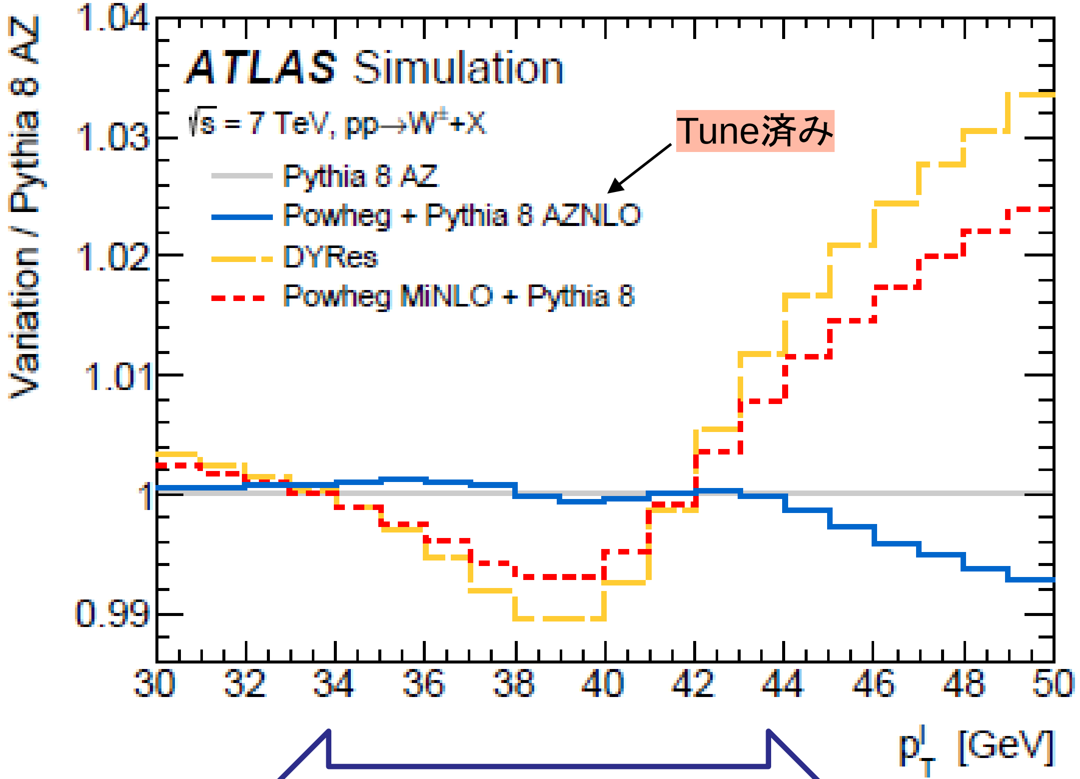
PT(W) – predictions with other sets

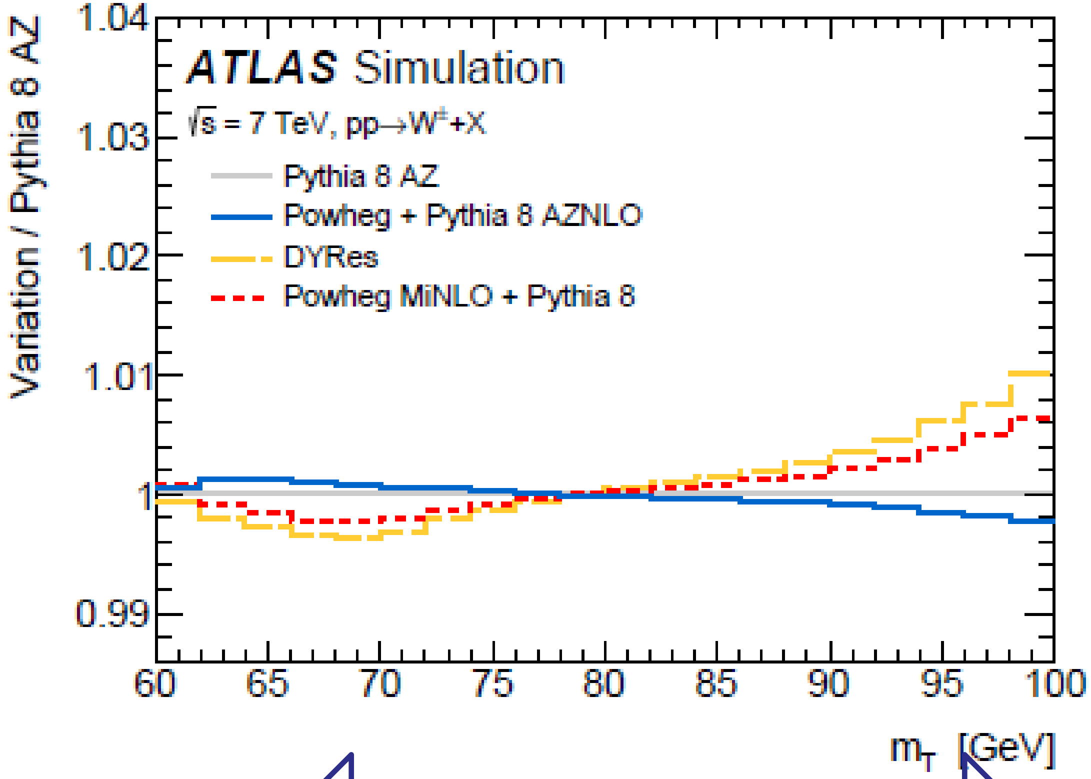
$p_T^{miss} > 30$ GeV

$u_T < 30$ GeV

$m_T > 60$ GeV

Pt(W) 分布をいくつかの generators でそれぞれのdefault parametersを用いて比較
⇒lepton pT と mT 分布を Pythia8 AZ tuneを基準として比較
⇒違いが大きくならない領域をフィット領域として W massを求める





32-45 GeV

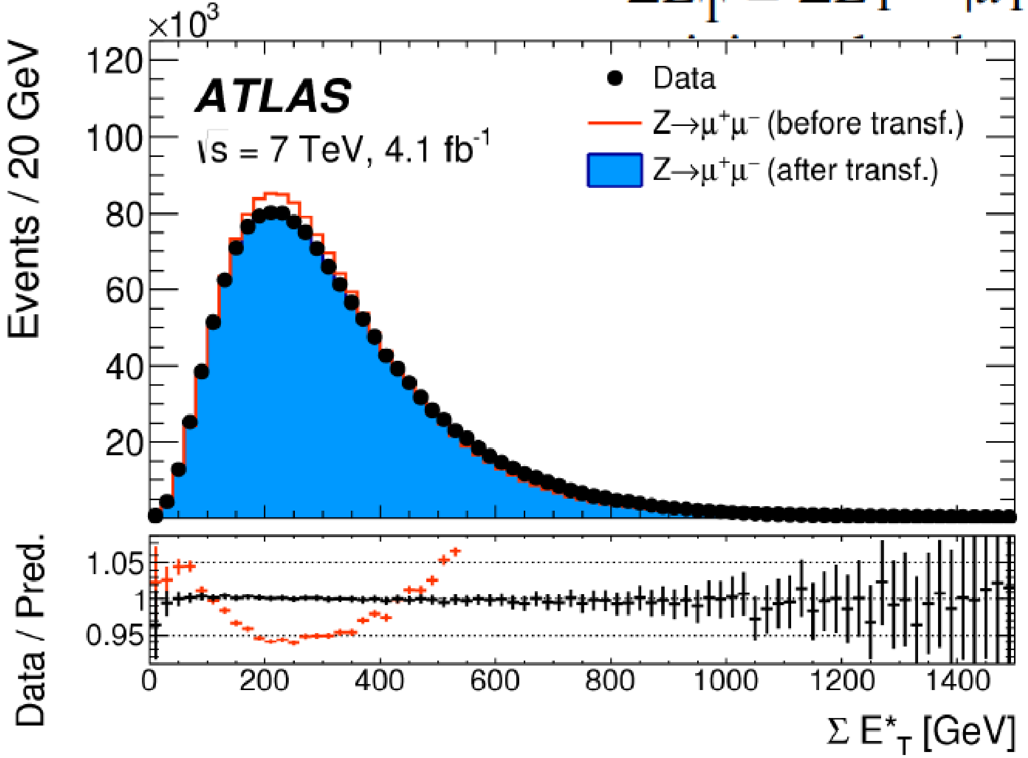
66-99 GeV

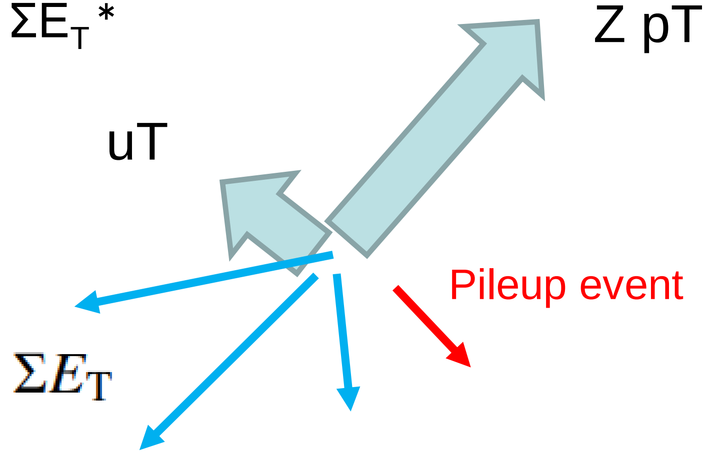
パラメータは特定のgenerator(Pythia 8 AZ)を用いて決定したものなので、他との違いは不定性に含まない
⇒ Recoil QCD modelingにおける不定性として考慮: PDF uncertainty is dominant

Recoil hadronic activity

- pile-up 事象を MC に入れ、データと一致するよう、ΣE_T を補正→ ΣE_T *
- Z->μμ 事象のΣE_T *に合うようにスケールと分解能を補正

$$\Sigma E_T^* \equiv \Sigma E_T - |\vec{u}_T|$$

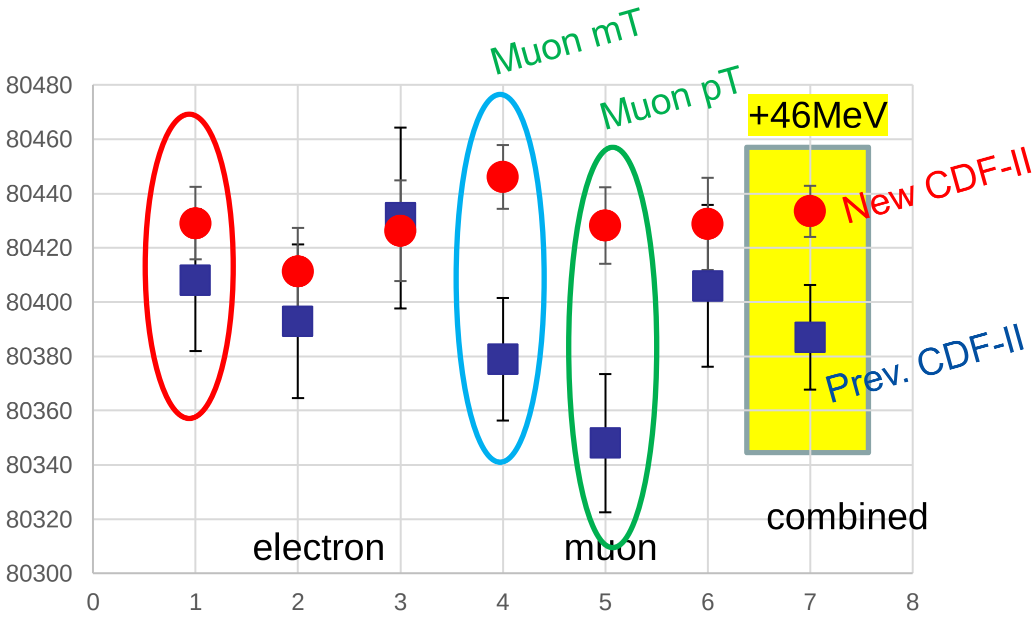




QCD:up to13MeV

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
ΣE_T^* correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \to W$ extrapolation)	0.2	5.8	0.2	4.3	0.2	5.1
Total	2.6	14.2	2.7	11.8	2.6	13.0

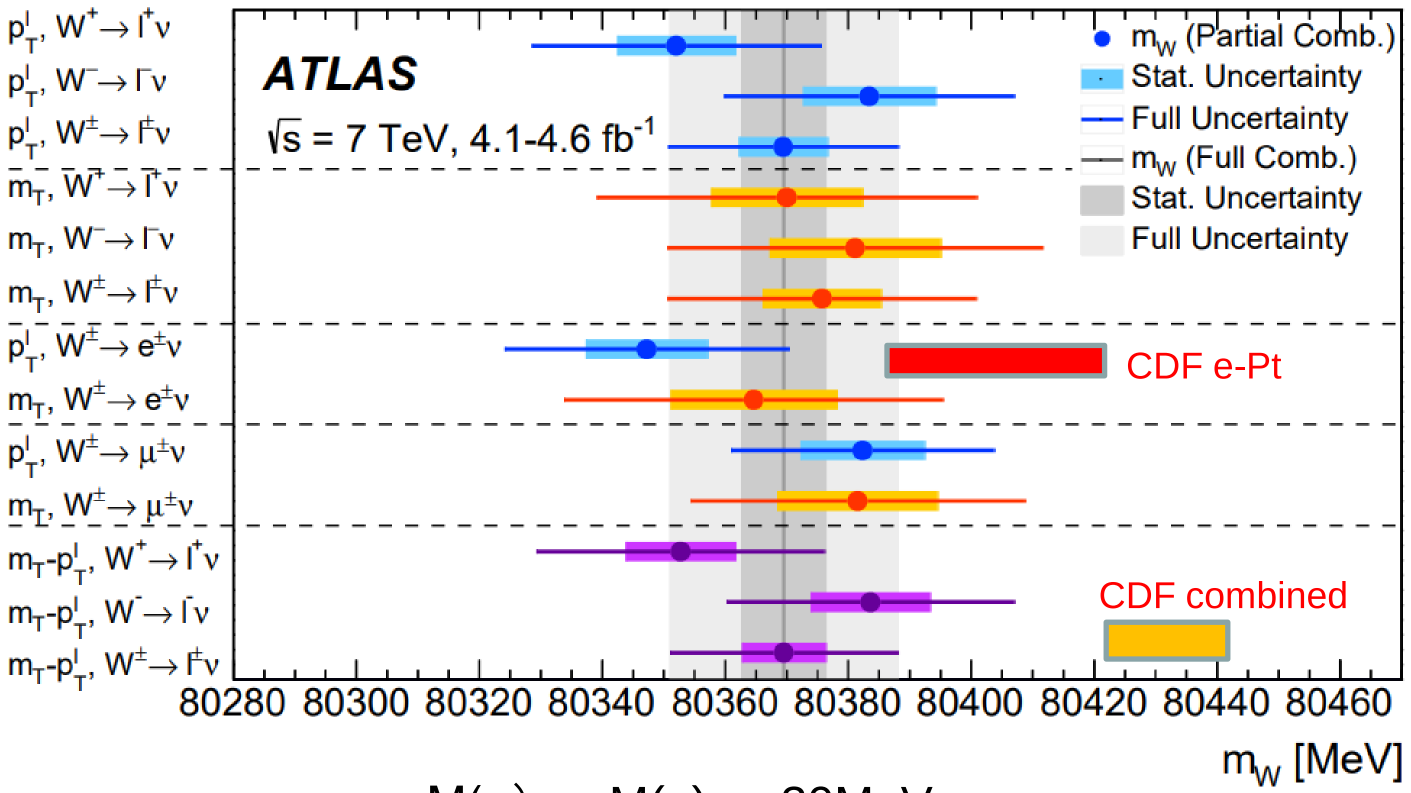
W mass CDF-II vs ATLAS



$80\,433.5 \pm 6.4_{stat} \pm 6.9_{syst}$ MeV

exp model

$80\,370 \pm 7_{stat} \pm 11_{syst} \pm 14_{syst}$ MeV

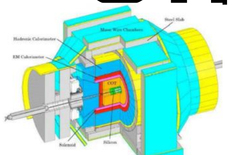


M(μ)－M(e) ~ 12MeV
M(－)－M(+)~ 8(μ)/-15(e)MeV

M(μ) － M(e) ~ 30MeV
M(－) － M(+)~20MeV

M(CDF)ーM(ATLAS)~ 73 MeV

Uncertainty in PDF 3.9MeV vs 9.2MeV



"PDF の理解度がこの10年で大きく向上"
ΔM_W: 10MeV⇒3.9MeV

NNPDF3.1 (NNLO) as default
"uncertainty" of PDF => **3.9 MeV**

他の PDF sets (NNLO)
- CT18
- MMHT2014
- NNPDF3.1

中心値は2.1 MeV以下で一致

他の PDF sets (NLO) - as a check
- ABMP16
- CJ15
- MMHT2014
- NNPDF3.1

中心値は3 MeV以下で一致

考慮していない高次のQCD effects ~ 0.4 MeV
- varying factorization/renormalization scales
- changing resummation/non-perturvative schema

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use CT10 (NNLO) as default
"uncertainty" of PDF
=> 14 MeV for W^+ /13 MeV for W^-

Total light-quark sea PDF is well constrained by DIS data
But u to d (s)-quark decomposition is less precisely known

⇒ PDF不定性によるm_T 分布は、W^+ と W^- で反相関

PDF 不定性はW^+ と W^- の和を取ると減少
=> 7.4 MeV

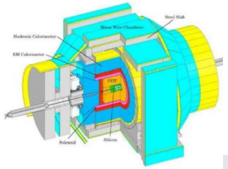
他の PDF sets (NNLO)
- CT14
- MMHT201

=> 3.8 MeV

考慮していない高次のQCD effects => small

Overall PDF uncertainty: 9.2 MeV

Uncertainty vs ATLAS



Source	Uncertainty (MeV)	ATLAS uncertainty
Lepton energy scale	3.0	6.6/6.4
Lepton energy resolution	1.2	
Recoil energy scale	1.2	2.9
Recoil energy resolution	1.8	
Lepton efficiency	0.4	
Lepton removal	1.2	
Backgrounds	3.3	4.5
p_T^Z model	1.8	8.3
p_T^W/p_T^Z model	1.3	
Parton distributions	3.9	9.2
QED radiation	2.7	5.5
W boson statistics	6.4	6.8
Total	9.4	19

ATLAS uncertainty

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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

Neutrino transverse momentum distribution not used

PYTHIA8 parameters tuning => QCD uncertainty

EWK uncertainty

Decay channel	$W \to e\nu$		$W \to \mu\nu$	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]				
FSR (real)	< 0.1	< 0.1	< 0.1	< 0.1
Pure weak and IFI corrections	3.3	2.5	3.5	2.5
FSR (pair production)	3.6	0.8	4.4	0.8
Total	4.9	2.6	5.6	2.6

Δ(LO-NLO) → Pure weak and IFI corrections

Material understanding → FSR (pair production)

2つの実験で大きな違いはPDF, QCD modeling, lepton energy scale, EWK

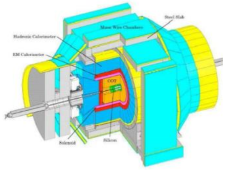
Z stat.

Material understanding

pp collider

?

Number of W/Z events



σB is about 10:1 for W:Z

Sample	Candidates
W → electron	1 811 700
Z → electrons	66 180
W → muon	2 424 486
Z → muons	238 534

$\|\eta_\ell\|$ range	0–0.8	0.8–1.4	1.4–2.0	2.0–2.4	Inclusive
$W^+ \to \mu^+\nu$	1 283 332	1 063 131	1 377 773	885 582	4 609 818
$W^- \to \mu^-\bar{\nu}$	1 001 592	769 876	916 163	547 329	3 234 960
$\|\eta_\ell\|$ range	0–0.6	0.6–1.2		1.8–2.4	Inclusive
$W^+ \to e^+\nu$	1 233 960	1 207 136		956 620	3 397 716
$W^- \to e^-\bar{\nu}$	969 170	908 327		610 028	2 487 525

TABLE VIII. Effect of selection cuts.

e-channel

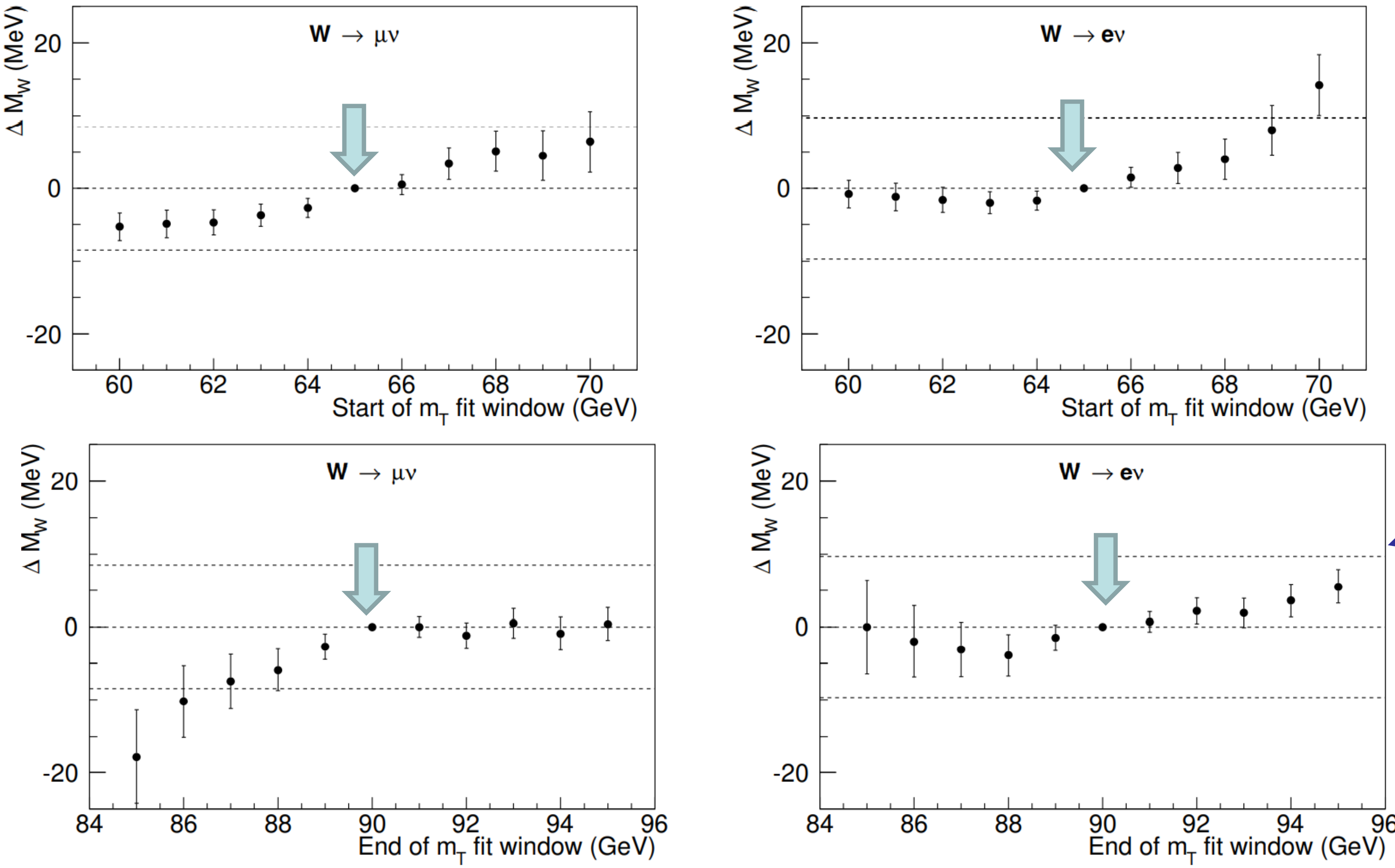
Criterion	W events after cut	Z events after cut
Initial sample	108455	19527
Z vertex requirement	101103	16724
Fiducial requirements	74475	9493
Tracks through all CTC superlayers	71877	8613
$E_T^e > 25$ GeV	67007	6687
$E_T^\nu > 25$ GeV	55960	N/A
$\|\mathbf{u}\| < 20$ GeV	46910	N/A
$P_T^e > 15$ GeV	45962	5257
N_{tracks} in the electron towers$=1$	43219	1670
$M_{e,\text{track}} < 1$ GeV	43198	N/A
Not a Z candidate	42588	N/A
Opposite sign	N/A	1652
Mass fit region	30115	1559

Table from 2001 W-mass measurement PRD (D64.052001). In electron channel, Ntrk=1 requirement is critical for Z→ee events

W events
5.88×10^6 electron channel
7.84×10^6 muon channel

Z events
0.58×10^6 electron channel
1.23×10^6 muon channel

CDF: Effect of mass fit window



Error bar: expected from statistics variation wrt nomial

Deviation from = 0 is within expectation

Overall mass error 9 MeV

CDF: Sub-sample/time dependence

TABLE S10: Differences (in MeV) between W-mass p_T^ℓ-fit results and Z-mass fit results obtained from subsamples of our data with equal statistics. For the spatial and time dependence of the electron channel fit result, we show the dependence with (without) the corresponding cluster energy calibration using the subsample E/p fit.

Fit difference	Muon channel	Electron channel
$M_W(\ell^+) - M_W(\ell^-)$	$-7.8 \pm 18.5_{\rm stat} \pm 12.7_{\rm COT}$	$14.7 \pm 21.3_{\rm stat} \pm 7.7^{\rm E/p}_{\rm stat}$ $(0.4 \pm 21.3_{\rm stat})$
$M_W(\phi_\ell > 0) - M_W(\phi_\ell < 0)$	$24.4 \pm 18.5_{\rm stat}$	$9.9 \pm 21.3_{\rm stat} \pm 7.5^{\rm E/p}_{\rm stat}$ $(-0.8 \pm 21.3_{\rm stat})$
$M_Z(\text{run} > 271100) - M_Z(\text{run} < 271100)$	$5.2 \pm 12.2_{\rm stat}$	$63.2 \pm 29.9_{\rm stat} \pm 8.2^{\rm E/p}_{\rm stat}$ $(-16.0 \pm 29.9_{\rm stat})$

with (w/o) subsample/time dependent E/p calibration

Momentum scale from Υ→μμ

Time $$\left(\frac{\Delta p}{p}\right)_{\rm later} - \left(\frac{\Delta p}{p}\right)_{\rm earlier} = (23 \pm 22_{\rm stat})\ \text{ppm}$$

Luminosity $$\left(\frac{\Delta p}{p}\right)_{\rm higher} - \left(\frac{\Delta p}{p}\right)_{\rm lower} = (22 \pm 22_{\rm stat})\ \text{ppm}$$

Discussion

CDF II Improvements from previous publication

statistics: 4-fold increase (uncertainty: 12⇒6.4MeV)

systematics (uncertainty: 15⇒6.9MeV)

- lepton scale uncertainty from 7⇒3.0MeV (unc. associated to NBC/BC is understood and removed) new
- Theoretical model improvement: RESBOS (angular smearing, kurtosis of recoil energy), new
  PDF (ΔM=10⇒3.4MeV)
- new DYqT for p_T^W / p_T^Z difference
- …. (data driven calibration: improve with *L*)

previous CDF II 80,389±19 MeV

new value $M_W = 80{,}433.5 \pm 9.4\,\mathrm{MeV}$

Δ=+44.5 MeV

lepton energy scale: +10 MeV
PDF: +3.5MeV
contributions from others not breakdown-able
More robust analysis than previous

+3.0σ

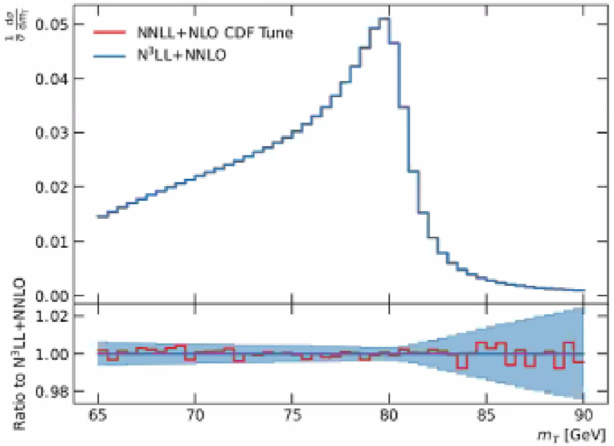
SM expectation: $M_W = 80{,}357 \pm 6\,\mathrm{MeV}$ +7.0σ

ATLAS value: 80 370±19 MeV

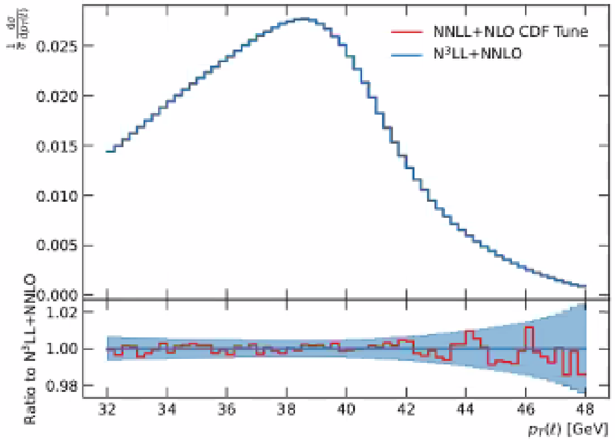
J. Isaacson @KEK workshop 10 May 2022 2205.02788 [hep-ph]

RESBOS uncertainty

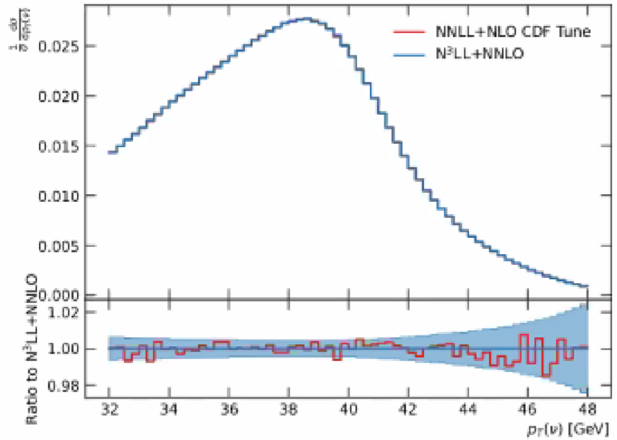
Results



Best Fit: $M_W = 80,386$ MeV



Best Fit: $M_W = 80,388$ MeV



Best Fit: $M_W = 80,389$ MeV

Resum. Pert.

CDF: NNLL(+NLO)

available: N^{3}LL(+NNLO)

	Mass Shift [MeV]	
Observable	ResBos2	+Detector Effect+FSR
m_T	1.5 ± 0.5	$0.2 \pm 1.8 \pm 1.0$
$p_T(\ell)$	3.1 ± 2.1	$4.3 \pm 2.7 \pm 1.3$
$p_T(\nu)$	4.5 ± 2.1	$3.0 \pm 3.4 \pm 2.2$

Red=simulated ratio CDF/REBOS2

Blue=stat uncertainty of CDF data

① Tune pT(Z) simulation data a la CDF

② extract W mass for “available” higher order sim data

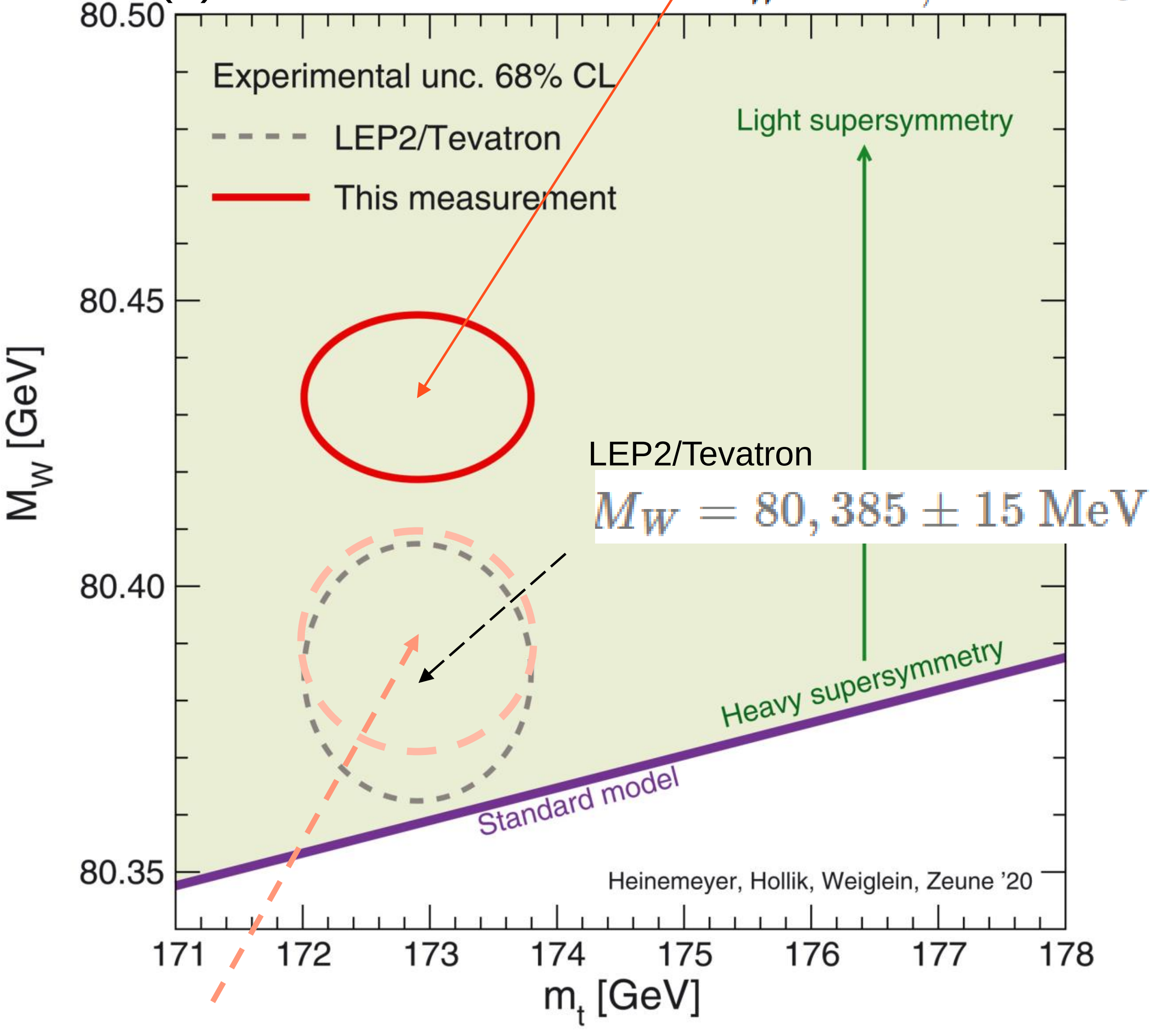
Shits are consistent with 0 MeV and up to 10 MeV in worst case

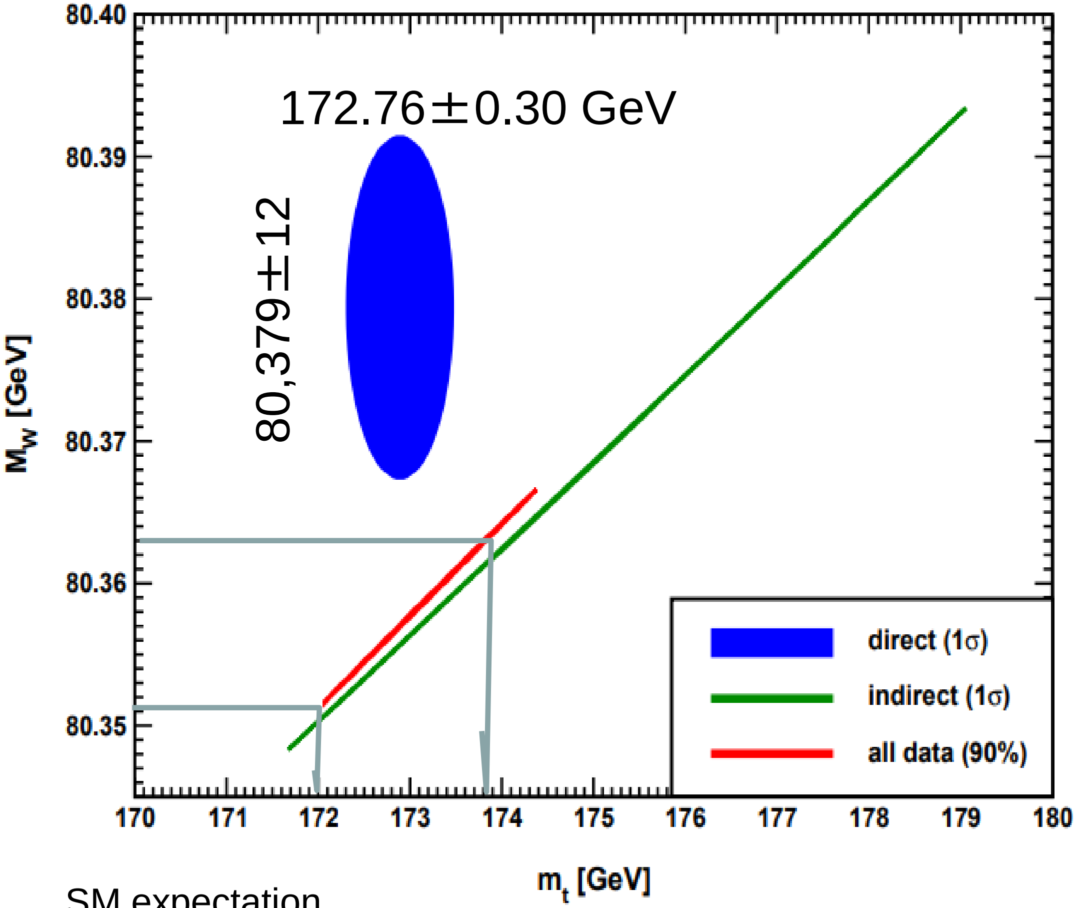
M_W vs M_{top} vs SM

(3) Science （2022） $M_W = 80{,}433.5 \pm 9.4\,\mathrm{MeV}$

(2) PDG2020

ATLAS measurement lowered LEP2/TeV M_W by 6 MeV uncertainty 15 →12 MeV





(1) 80,389±19 (previous CDF II)

SM expectation

$M_W = 80,357 \pm 6$ MeV

Summary

Personal view

- New W-mass measurement by CDF-II provides most precise value of

  $$M_W = 80{,}433.5 \pm 9.4\,\mathrm{MeV}$$

- The value is 7σ heavier than the SM expectation, 3.2σ heavier than the latest world average (PDG2022)
- The deviation should be explained by new physics (*e.g*. MSSM, 2HDM,…)
- Coordinated understanding of the LHC and CDF-II is preferred
- The result should be examined by other experiments
  - LHC experiments with large sample of W's (precision limited?)
  - New e^+e^- collider