

加速器実験による 空気シャワーモデル制限 (レビュー)

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参考資料: UHECR2012 (Y.Itow, R.Engel, T.Pierog)

(宇宙線relatedな) 加速器実験

赤字は現在も運転中

➤ 固定標的(fixed-target)実験 (2次 π , ν ビーム, 炭素標的等可)

— CERN PS

- HARP

— CERN SPS (400GeV proton primary)

- NA49/NA61(SHINE)

— ニュートリノ実験は省略

➤ (ハドロン)衝突型加速器(collider)

— CERN LHC (p-p $\sqrt{s}=14\text{TeV}$ (現在8TeV); Ion collision)

- ATLAS/ALICE/CMS/LHCb/TOTEM/LHCf (/MoEDAL)

— FNAL Tevatron (p- p_{bar} $\sqrt{s}=1.8\text{TeV}$);

- Cross sections by E710/CDF/E811

— BNL RHIC (p-p $\sqrt{s}=500\text{GeV}$, Ion collision);

— CERN SpS (p- p_{bar} $\sqrt{s}=630\text{GeV}$);

- UA1/UA2/UA4/UA5/UA7

— CERN ISR (p-p $\sqrt{s}=50\text{GeV}$);

加速器で何をみるか？

1. 非弾性衝突断面積
(平均衝突距離)

2. 粒子生成

Leading baryons

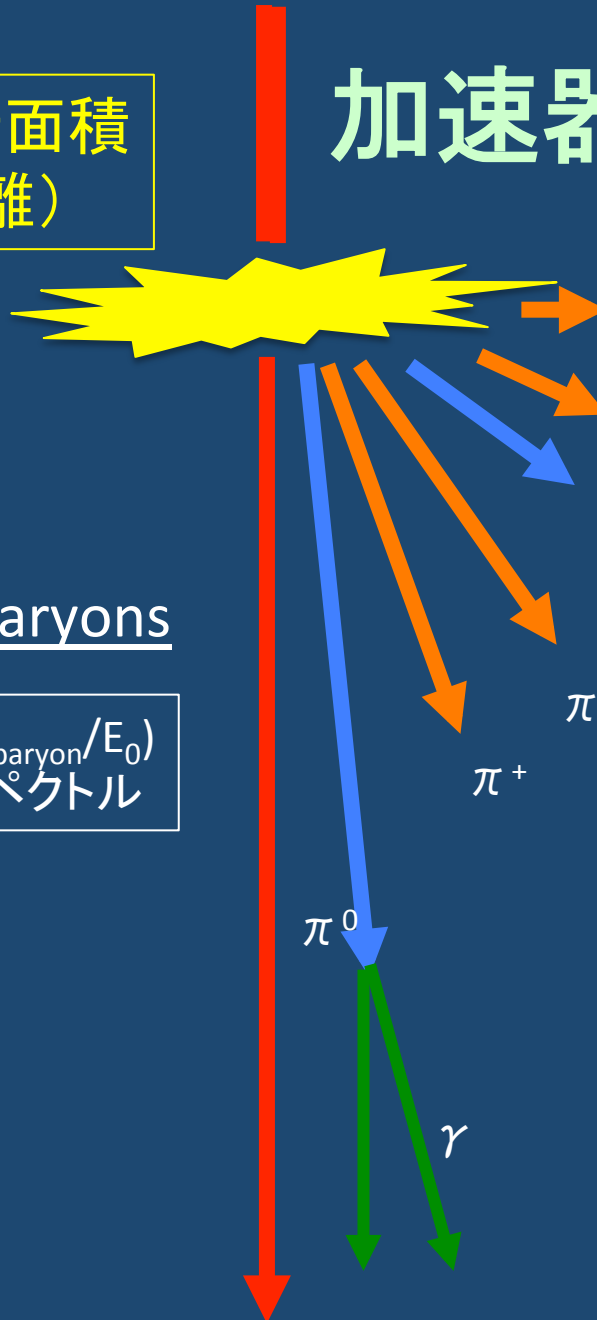
弾性度 (E_{baryon}/E_0)
Baryonスペクトル

中間子多重発生

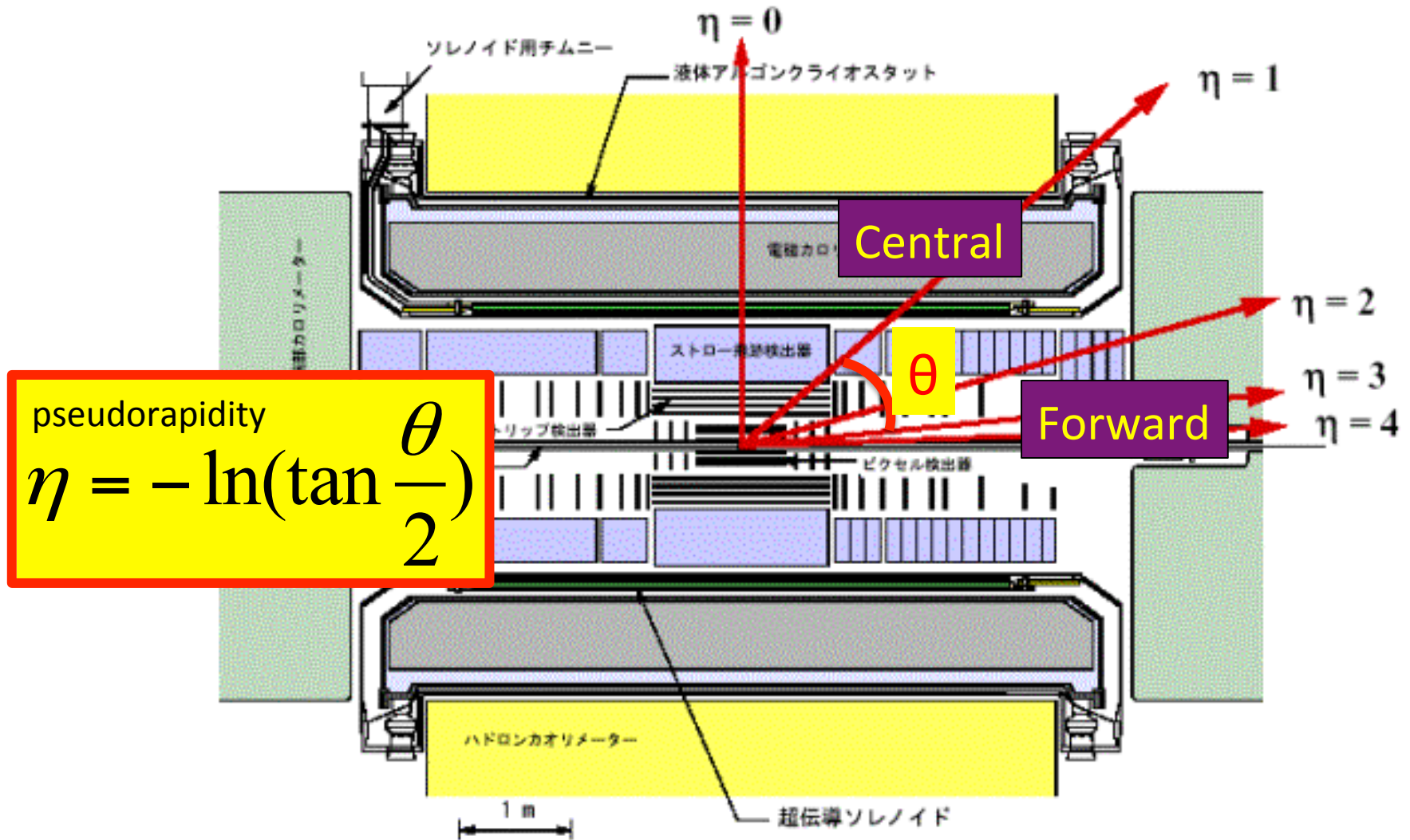
非弾性度 ($E_{\text{meson}}/E_0 = 1 - \text{弾性度}$)
粒子多重度(multiplicity)
Mesonスペクトル

3. 原子核効果

陽子 / 中性子



Collider experiment and pseudorapidity



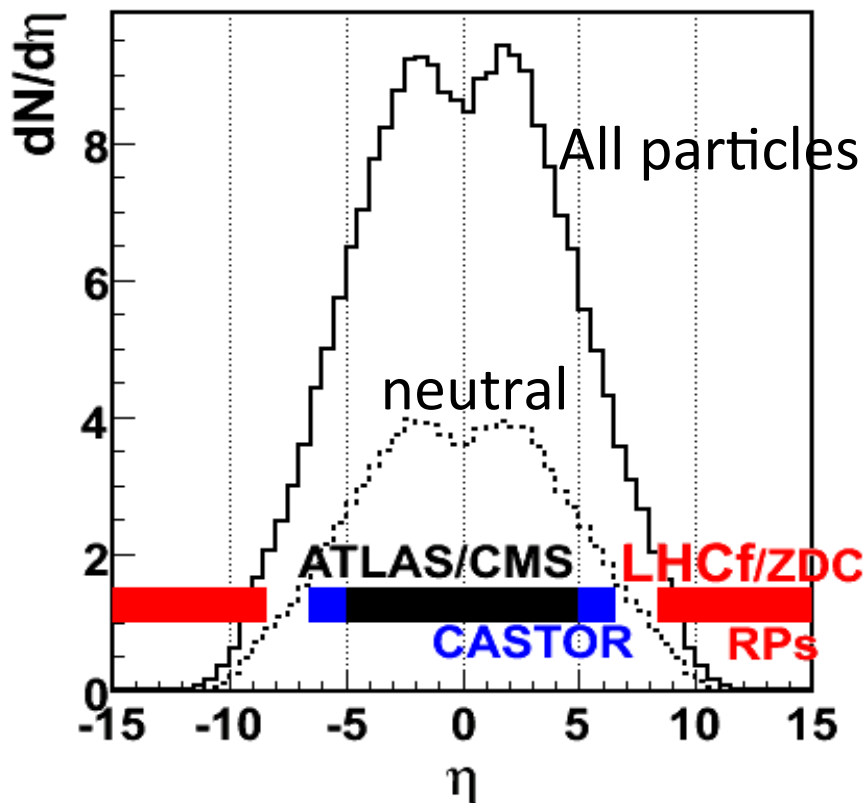
η : pseudorapidity $\sim y$: rapidity $y = (1/2) \times \ln((E+p_z)/(E-p_z))$
 Lorentz変換で、 $y \Rightarrow y + \text{const}$

衝突型加速器(Collider)のどこで測るか？

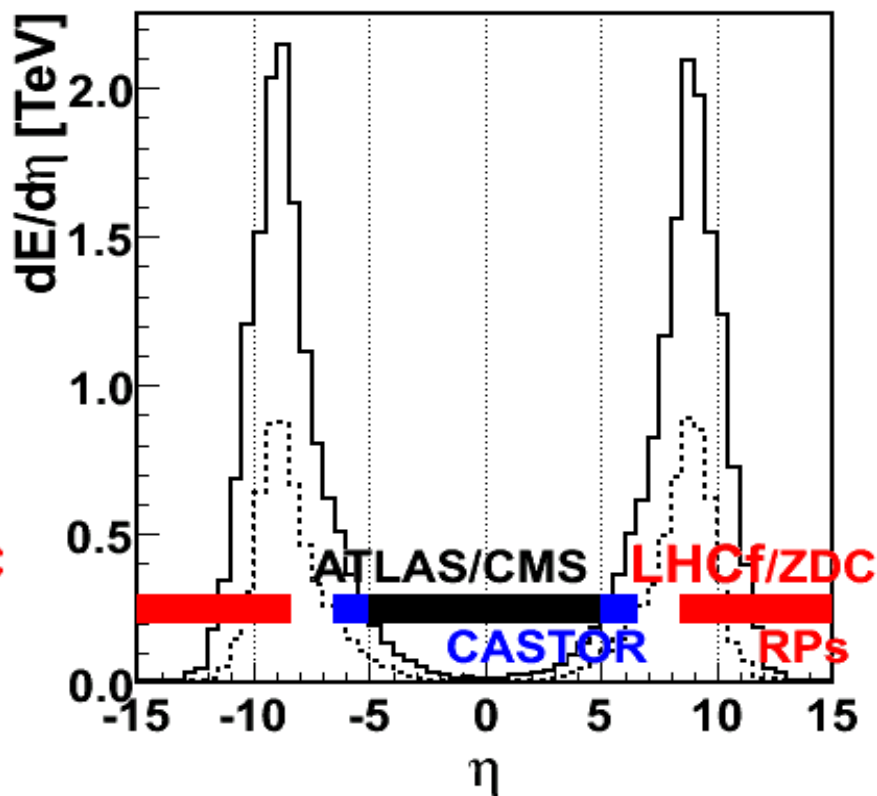
multiplicity and energy flux at LHC **14TeV** collisions

pseudo-rapidity; $\eta = -\ln(\tan(\theta/2))$

粒子多重度



エネルギー流量



ほとんどの粒子は中央へ、
ほとんどのエネルギーは**前方へ**

1. (全)非弾性断面積

LHC TOTEM σ_{inel}

EPL, 95 (2011) 41001

[光学定理]

$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \frac{1}{L} \left. \frac{dR_{el}}{dt} \right|_{t=0}$$

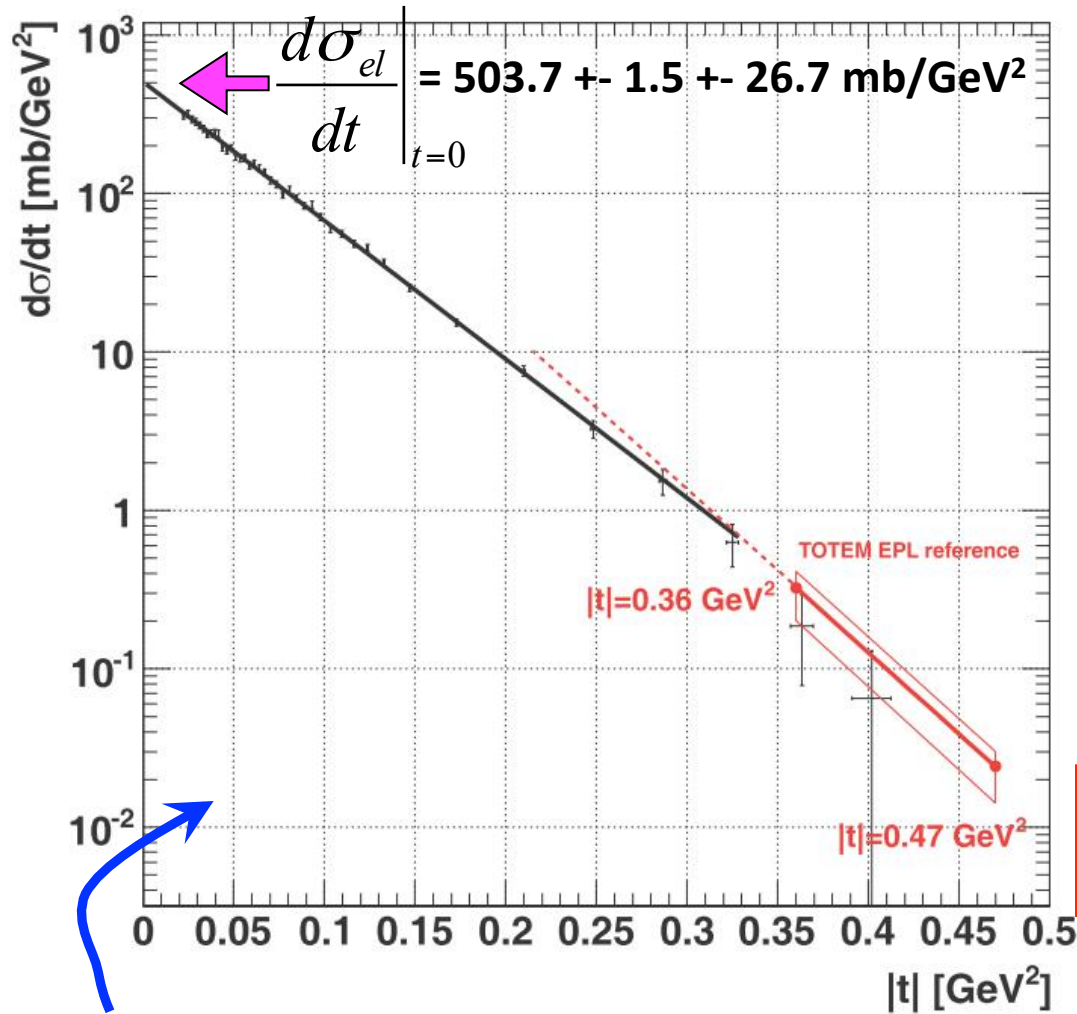
$$\rho = 0.14^{+0.01}_{-0.08}$$

(COMPETE collaboration)



$$\sigma_{tot} = 98.3 \pm 0.2^{+2.8}_{-2.7} mb$$

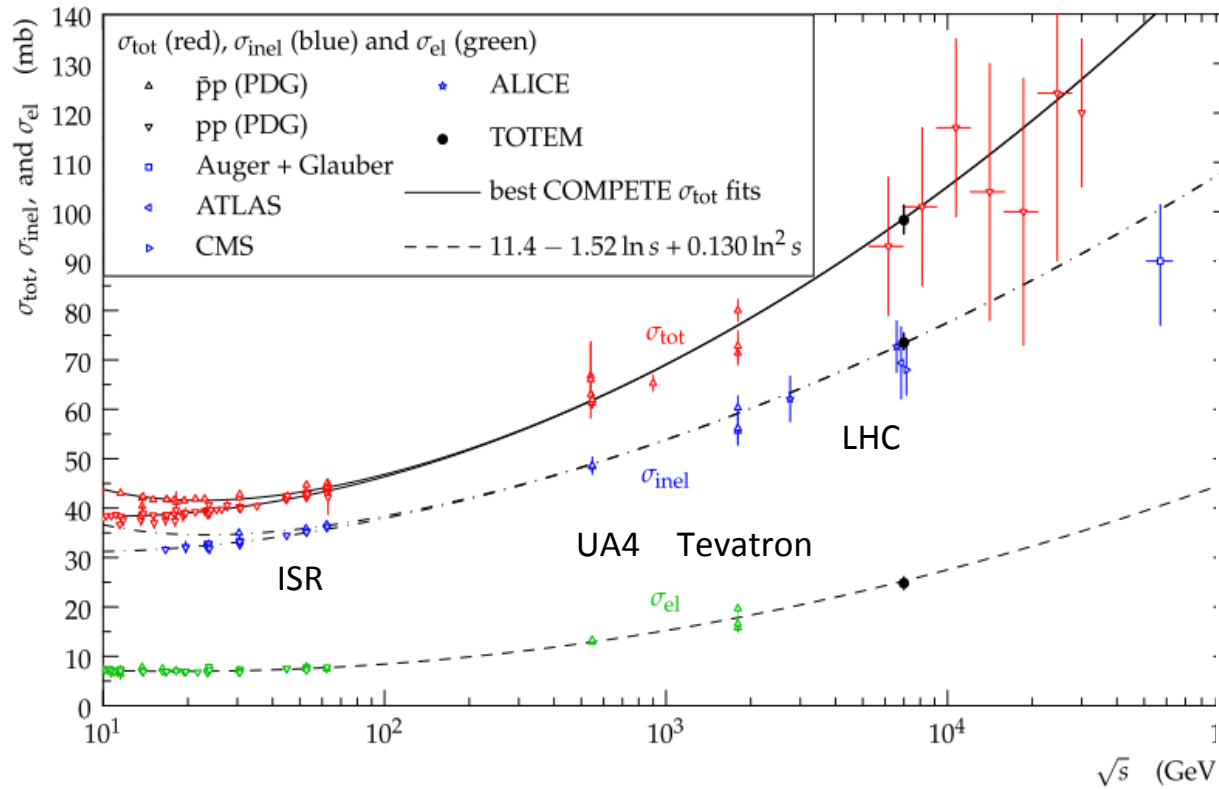
$$\begin{aligned} \sigma_{inel} &= \sigma_{tot} - \sigma_{el} \\ &= \underline{73.5 \pm 0.6^{+1.8}_{-1.3} mb} \end{aligned}$$



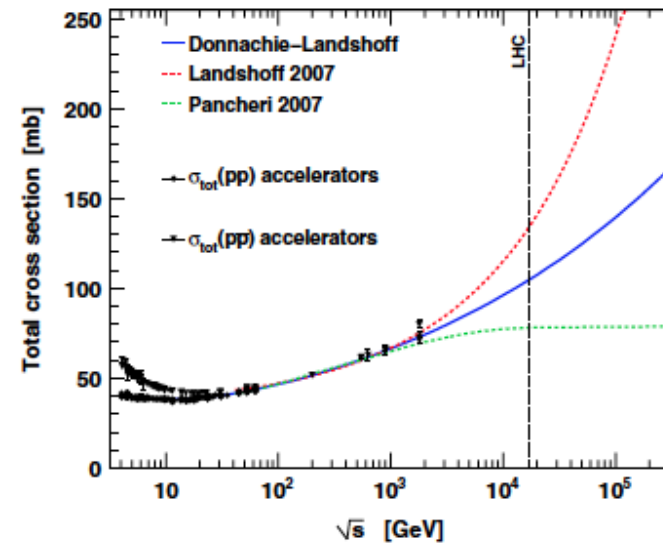
Integrated over entire “t” region

$$\sigma_{el} = \int \frac{d\sigma_{el}}{dt} dt = 24.8 \pm 0.2 \pm 1.2 mb$$

σ_{inel} result @ 7TeV



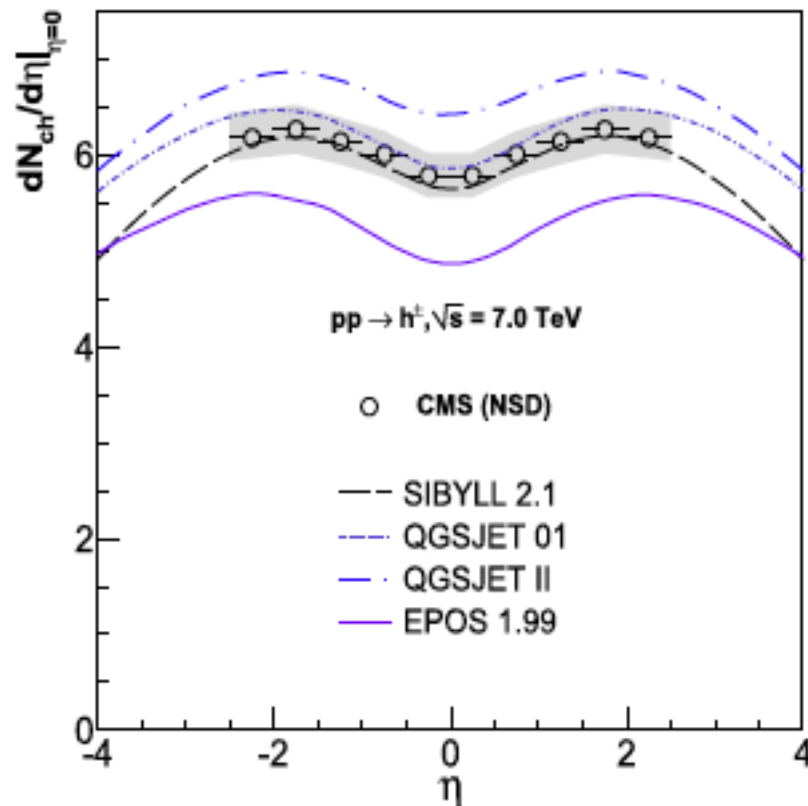
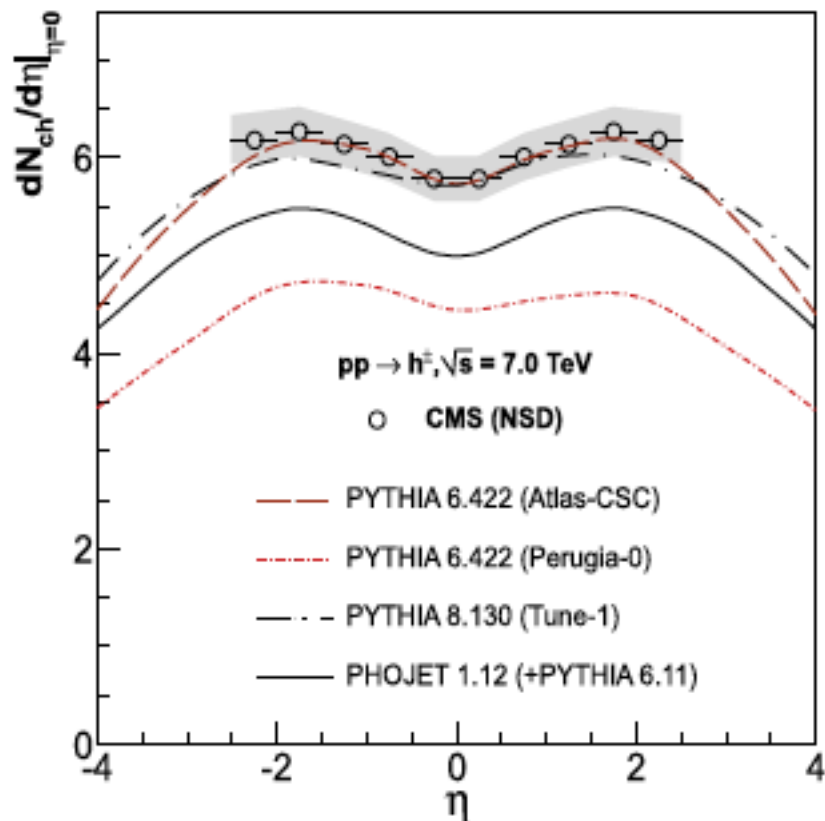
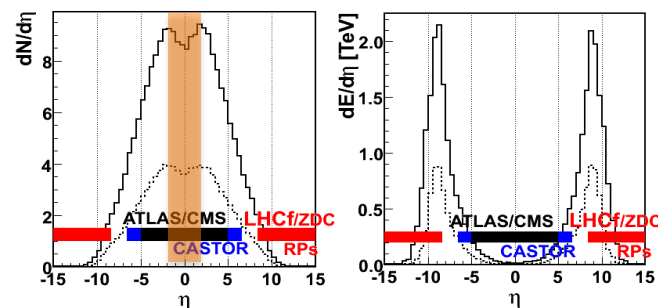
(Ulrich, PRD, 2011)



TOTEM	73.5+/-0.6+1.8-1.3 mb	d σ /dt(t=0)
ATLAS	69.4+/-2.4+/-6,9 mb	MBTS sample
CMS	68.0+/-2.0+/-2.4+/-4 mb	Ntrk sample
ALICE	72.7+/-1.1+/-5.1 mb	VZERO sample

2. 粒子生成

メソン多重度@central

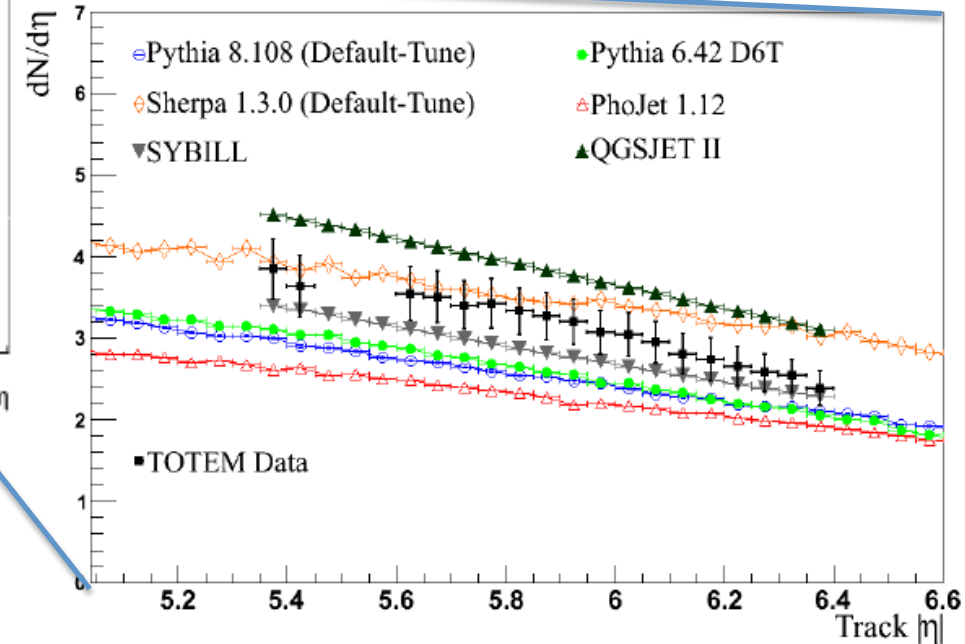
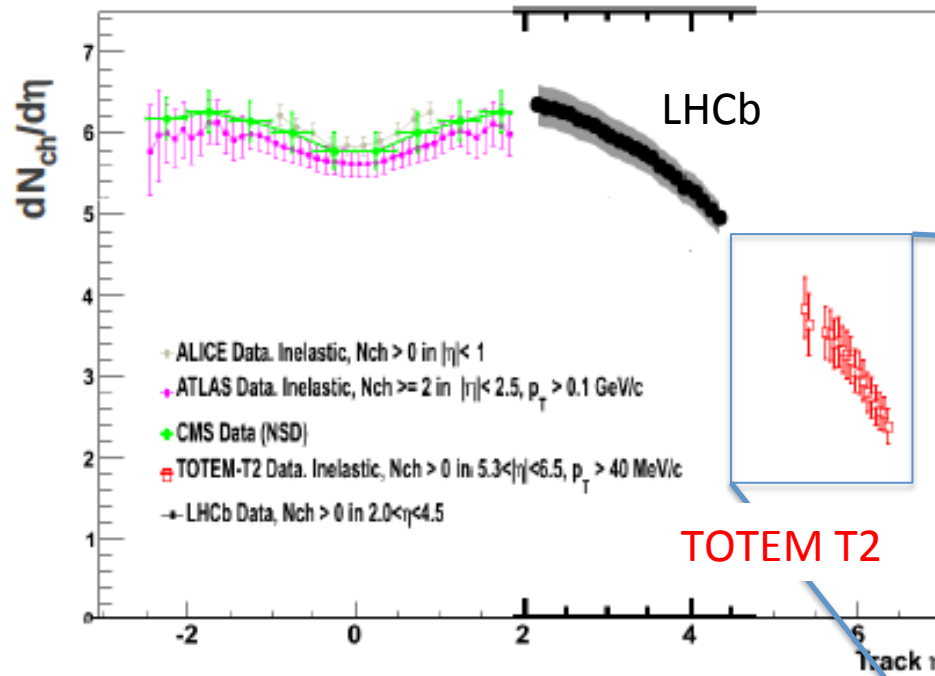
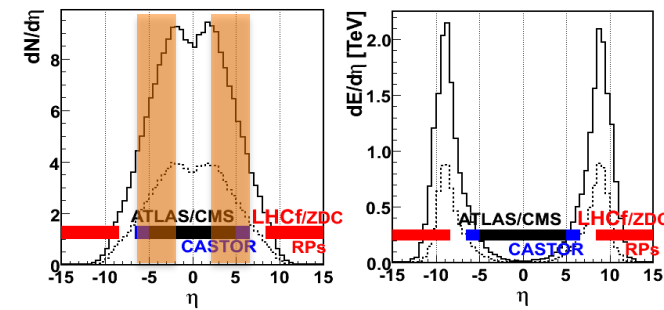


D.D'Enterria et al., Astropart. Phys., 35 (2011) 98-113

前方tracker, カロリメータ

- TOTEM T2 (EPL, 98 (2012) 31002)
- LHCb (EPJC (2012) 72:1947)
- CMS HF (JHEP, 11 (2011) 148)
- CMS CASTOR ($\eta = 5.2-6.6$; preliminary)
- LHCf (arXiv;hep-ex/1205.4578)
- RHIC BRAHMS (arXiv:hep-ex/0701041)
- SppS UA7 (PLB, 242 (1990) 531-535)
- ISR (Nucl. Phys., B109 (1976) 347-356)

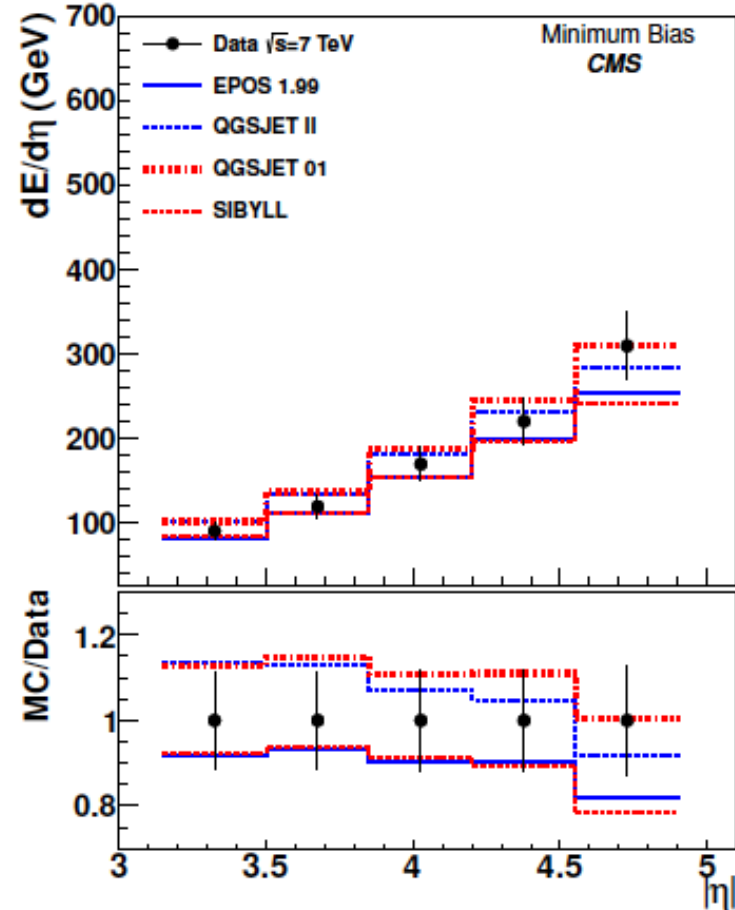
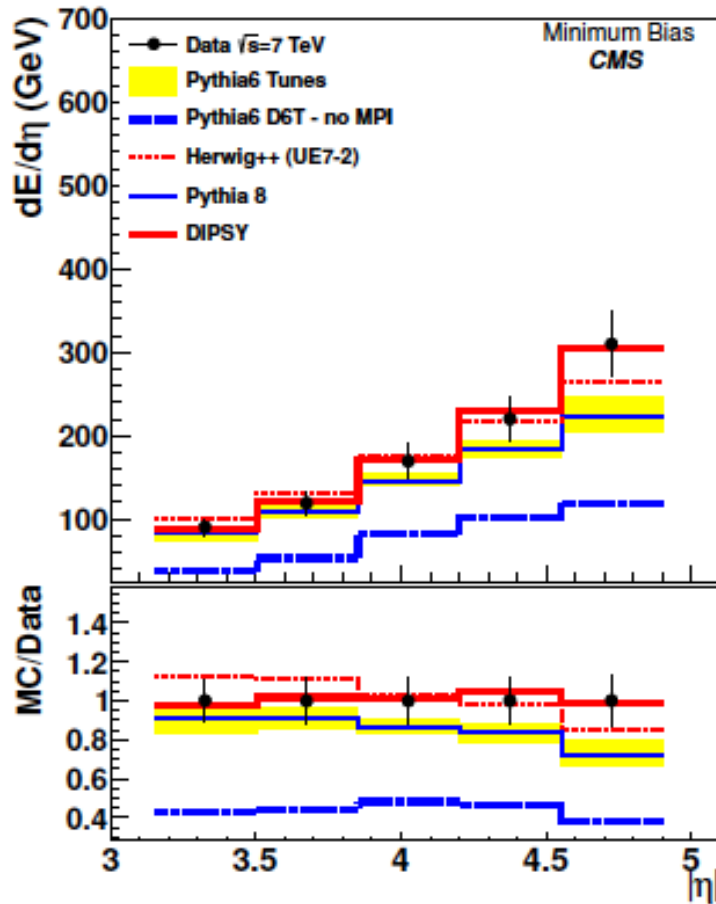
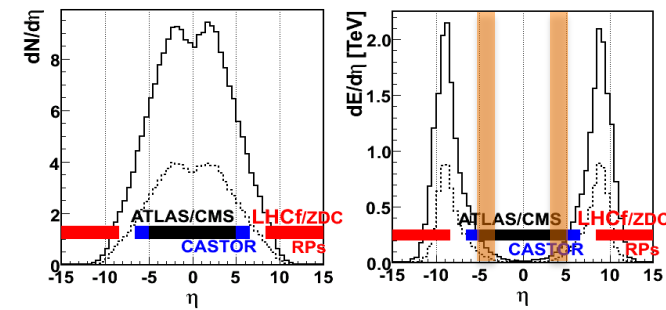
TOTEM T2 tracker, LHCb; 前方メソン多重度



Presentation at QCD at Cosmic Energies - V

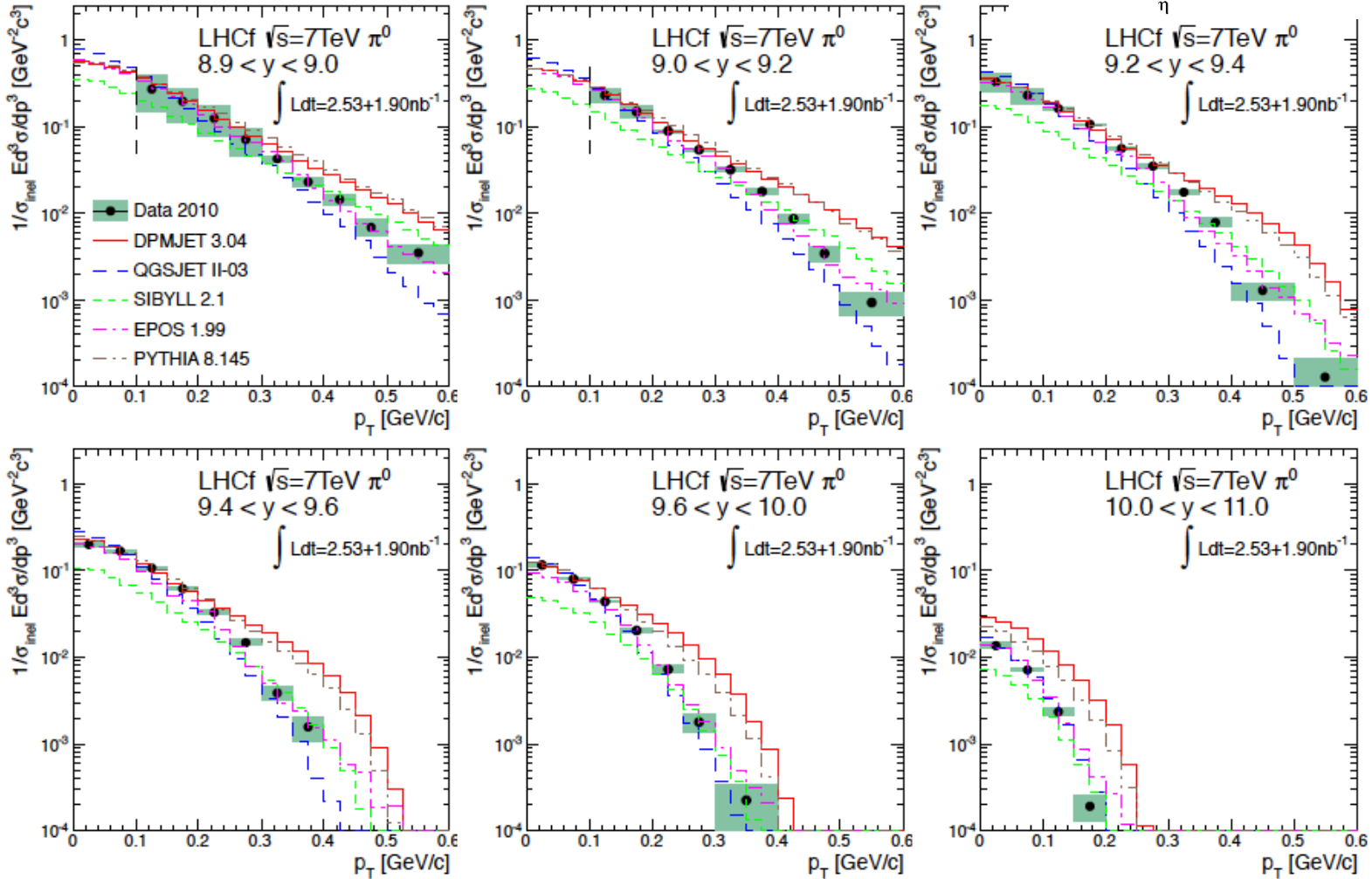
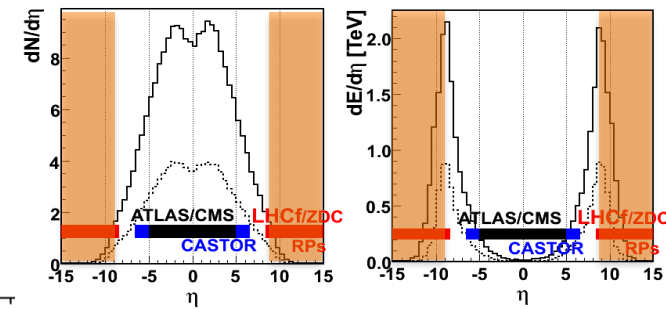
CMS HF

(Hadronic Forward Calorimeter)



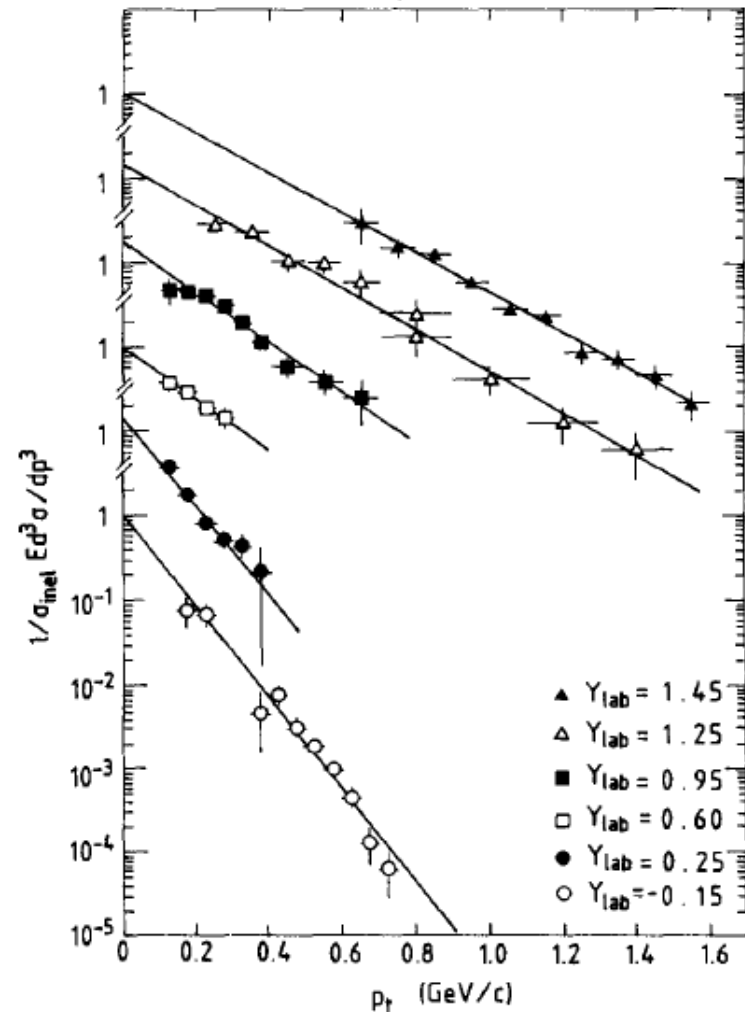
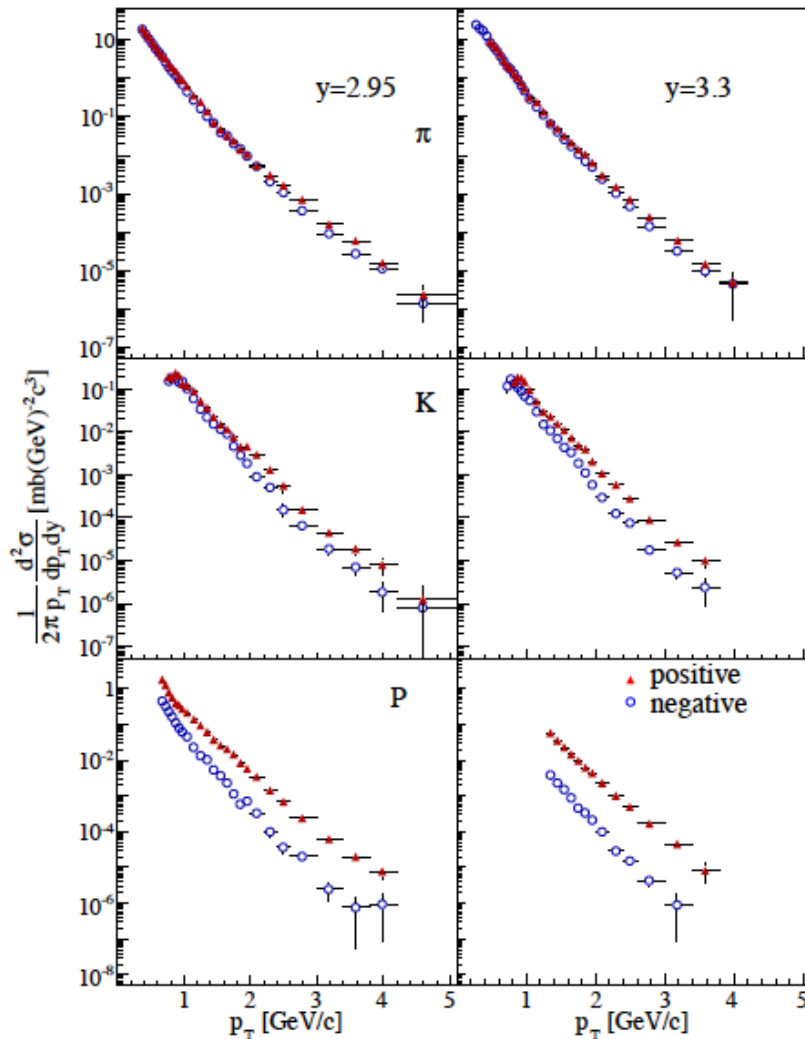
The CMS Collaboration, JHEP, 11 (2011) 148

LHCf; π^0 P_T 分布 (rapidity別)



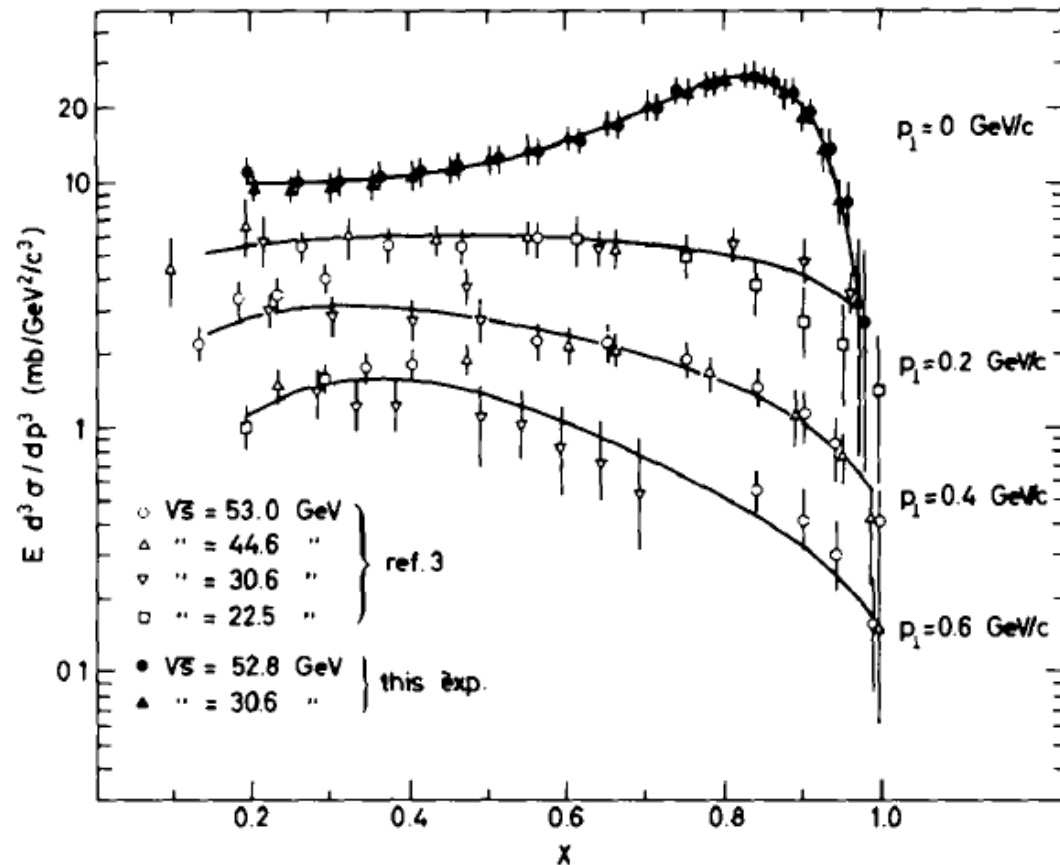
BRAHMS@RHIC (200GeV p-p)

UA7@SppS (630GeV p-p_{bar})



三ノイノノ四米上八

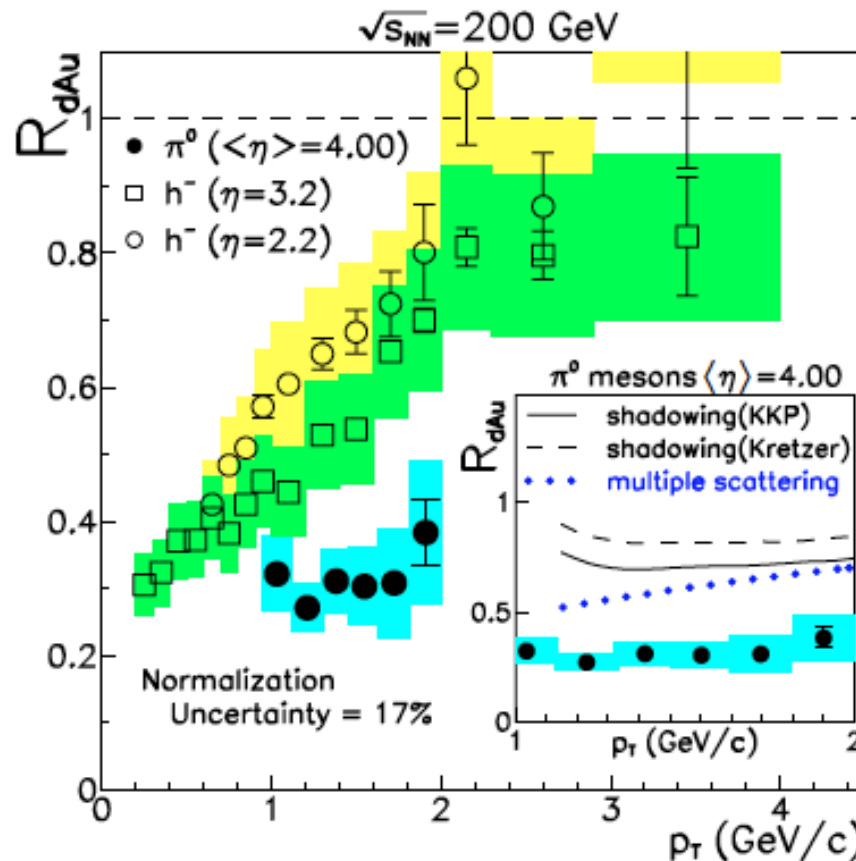
ISR前方中性子スペクトル



(注: HERA e-p collisionの前方中性子もある)

3. 原子核効果

RHIC d-Au $\sqrt{s_{NN}} = 200\text{GeV}$; 前方メソン



(The STAR Collaboration, PRL 97 (2006) 152302)

- RHIC d-Au以外、原子核衝突はこれまで重イオン(Pb, Au)のみ
- 今後、p(d)-重イオン、p(d)-軽イオンに注目

今後の加速器実験

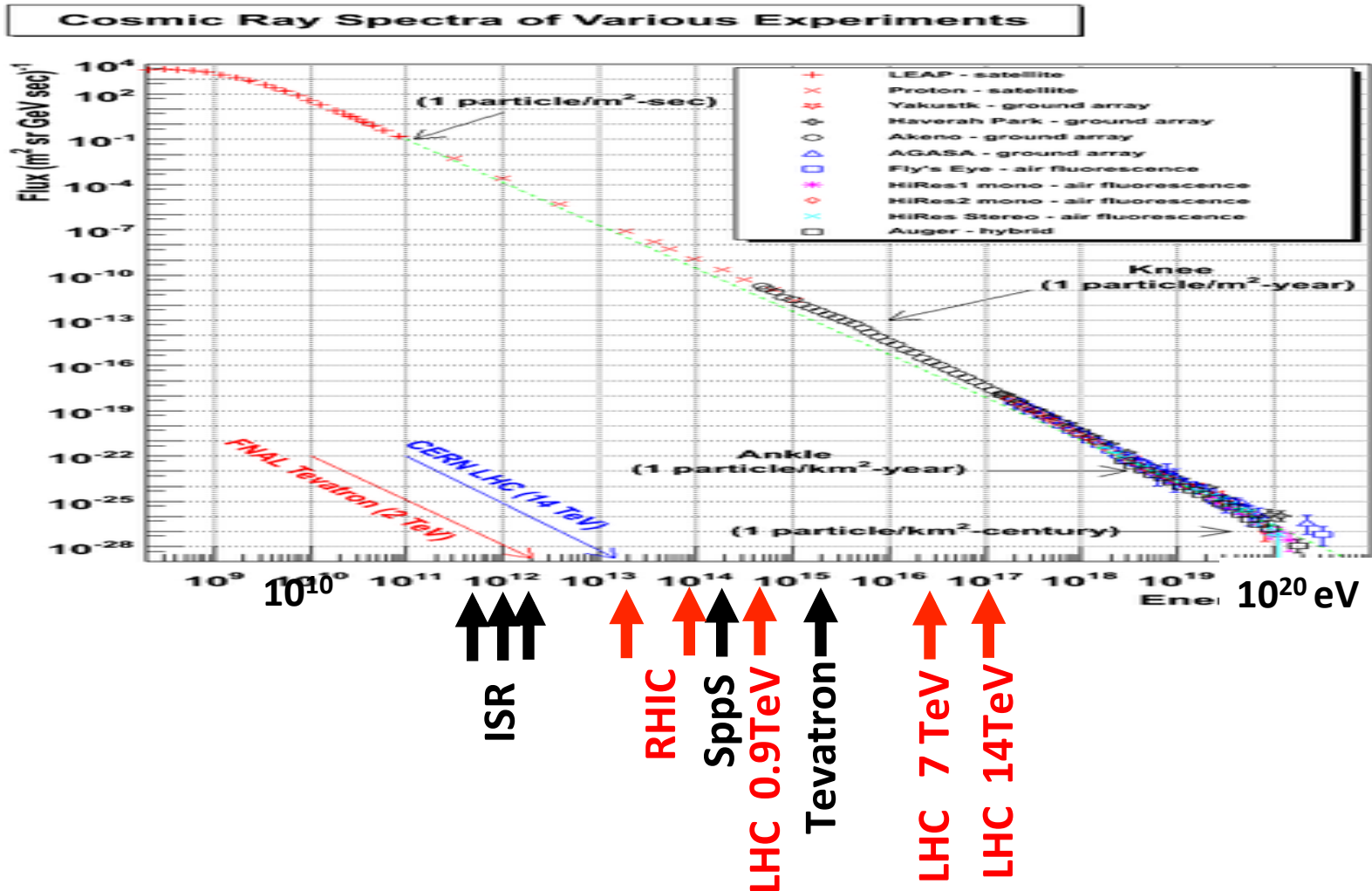
- LHC p-Pb
 - 2012年11月に実施 (3.5-4)Z TeV/beam
- LHC 14TeV p-p
 - 2014年後半 commissioning, 2015年- physics
 - $E_{\text{lab}}=10^{17}\text{eV}$ を実現

-
- RHIC p(d)-N; 議論開始
 - LHC N-N; 早くても10年後。その前に Arビーム。
 - LHC 33TeV??

まとめ

- 固定標的、衝突型実験共に宇宙線モデルの検証、改良に有効。特にLHCでは多くの実験が有効なデータを供給。
 - ✓ 非弾性衝突断面積 σ_{inel}
 - LHC TOTEMがよい精度で決定した
 - Central detector (エラー大)とずれ => diffractive eventの理解不足？
 - ✓ 粒子生成
 - 空気シャワーモデルの検証には、エネルギー流量の大きい前方測定が重要
 - LHCはハドロン衝突型加速器として初めて広いrapidityをカバー
 - ここまで宇宙線モデルがLHCの結果をよく再現している。LHC各実験グループも積極的に宇宙線モデルとの比較をすすめている。
 - 前方baryonのデータが少ない => LHCf
 - ✓ 原子核効果
 - 議論、データともに少ない => LHC p-Pb
- 将来
 - イベント毎の解析 (hard scatter/diffraction/...) は手つかず
 - LHCは今後 p-Pb衝突 (2012年11月)、14TeV衝突 (2014-2015年)を予定
 - 宇宙線研究のための原子核衝突(窒素衝突)は今後の課題

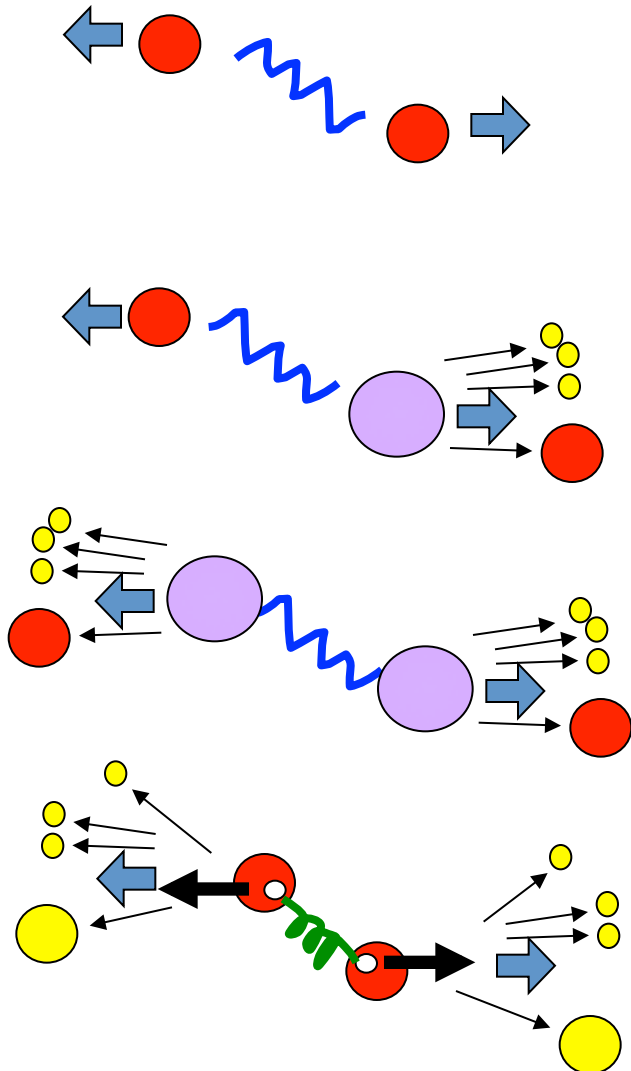
Cosmic ray spectrum & historical colliders



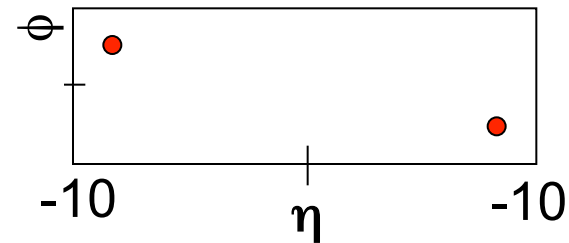
Backup

pseudorapidity and interactions

σ @7TeV

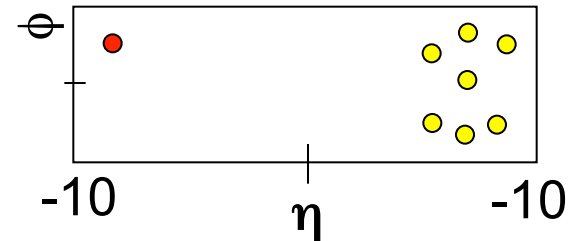


Elastic



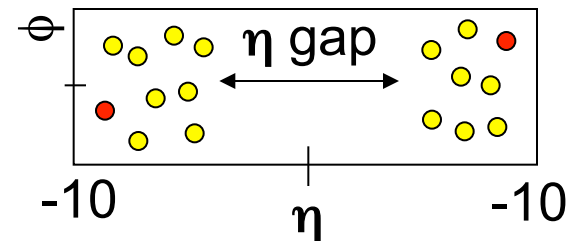
$\sim 25\text{mb}$

Single diffractive



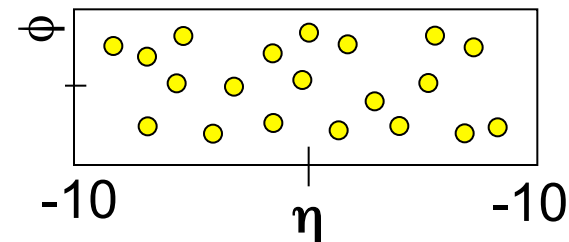
$\sim 10\text{mb}$

Double diffractive



$\sim 10\text{mb}$

Non-diffractive



$\sim 50\text{mb}$

A LHC detector and pseudorapidity

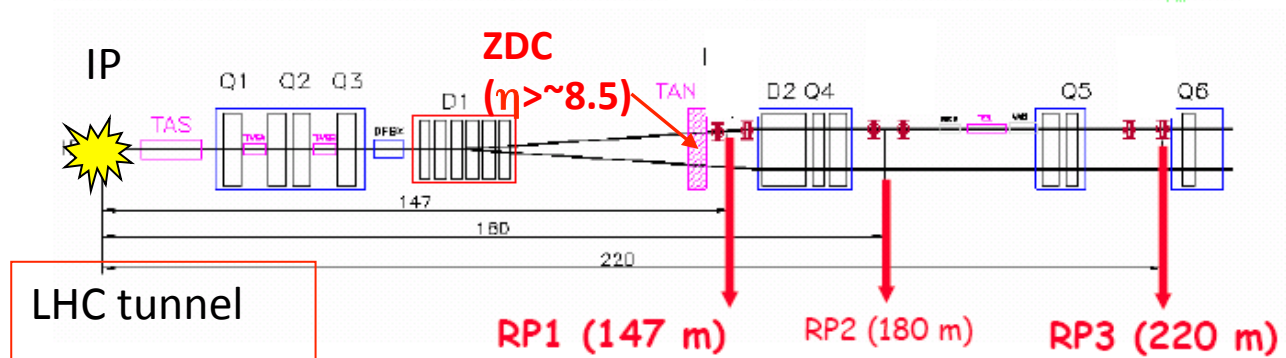
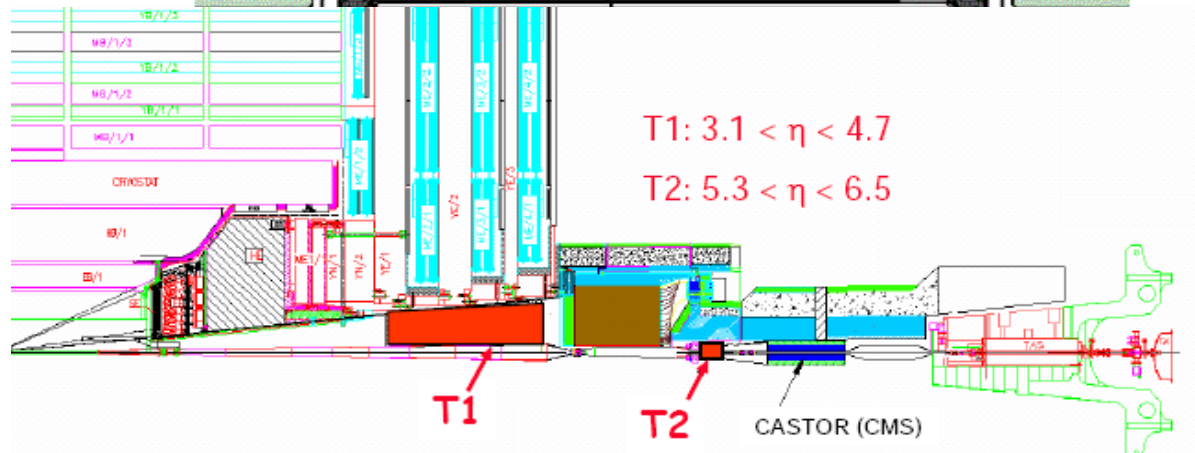
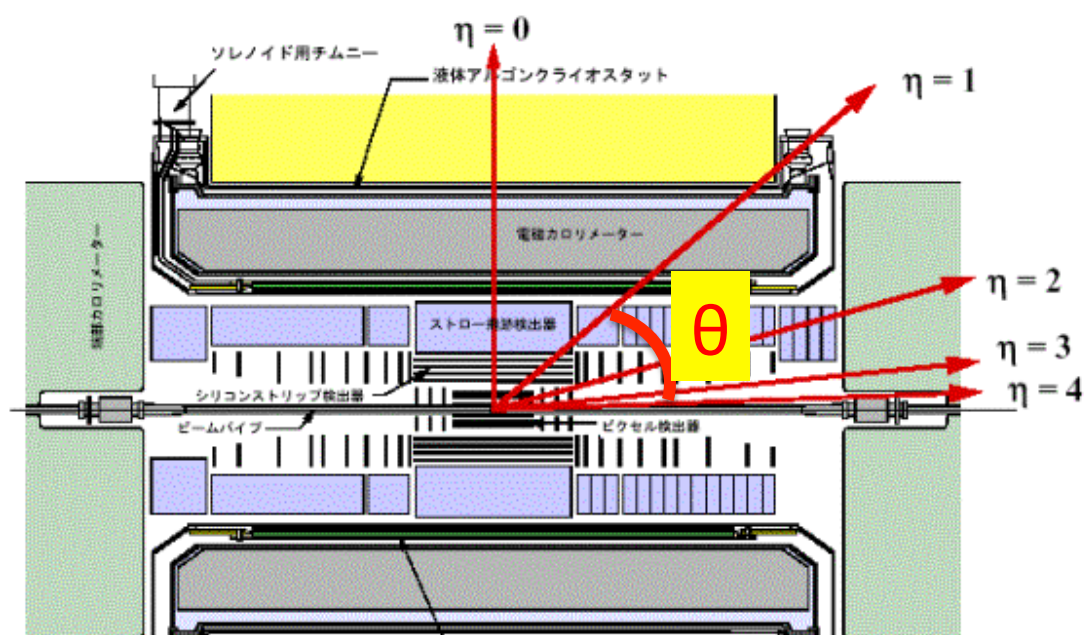
pseudorapidity

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

η : pseudorapidity
 $\sim y$: rapidity

$$y = (1/2) \times \ln((E+p_z)/(E-p_z))$$

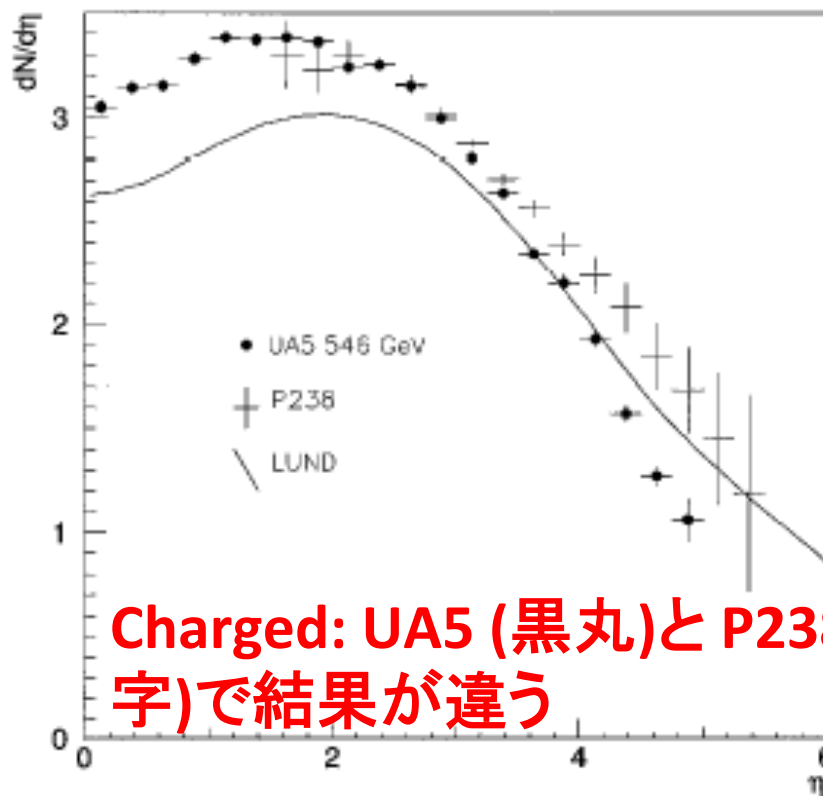
Lorentz変換で、
 $y = y + \text{const}$



加速器で何を見るか？

- (全)非弾性断面積
 - 超前方弾性散乱測定＋光学定理(TOTEM)
 - 全非弾性事象の測定(minimum bias event)
- 粒子生成
 - 中心のメソン多重度(multiplicity; central detectors)
 - (超)前方測定(forward calorimeters, ZDC, LHCf)
 - (超)前方Baryon測定(ISR)
- 原子核効果
 - 原子核衝突実験(これまで Pb-Pb, Au-Au, d-Au)

Pseudo rapidity distribution at SppS



Charged: UA5 (黒丸)と P238(十字)で結果が違う

Fig. 5. Final $dN_{ch}/d\eta$ result compared to the result from UA5 and the distribution generated by PYTHIA-JETSET. For the P238 points, only the shape errors are shown, the 5% normalization error is not plotted. The UA5 points are plotted with their statistical errors, a normalization uncertainty of order 2.5% is not shown. The Monte Carlo curve is unweighted for purposes of comparison.

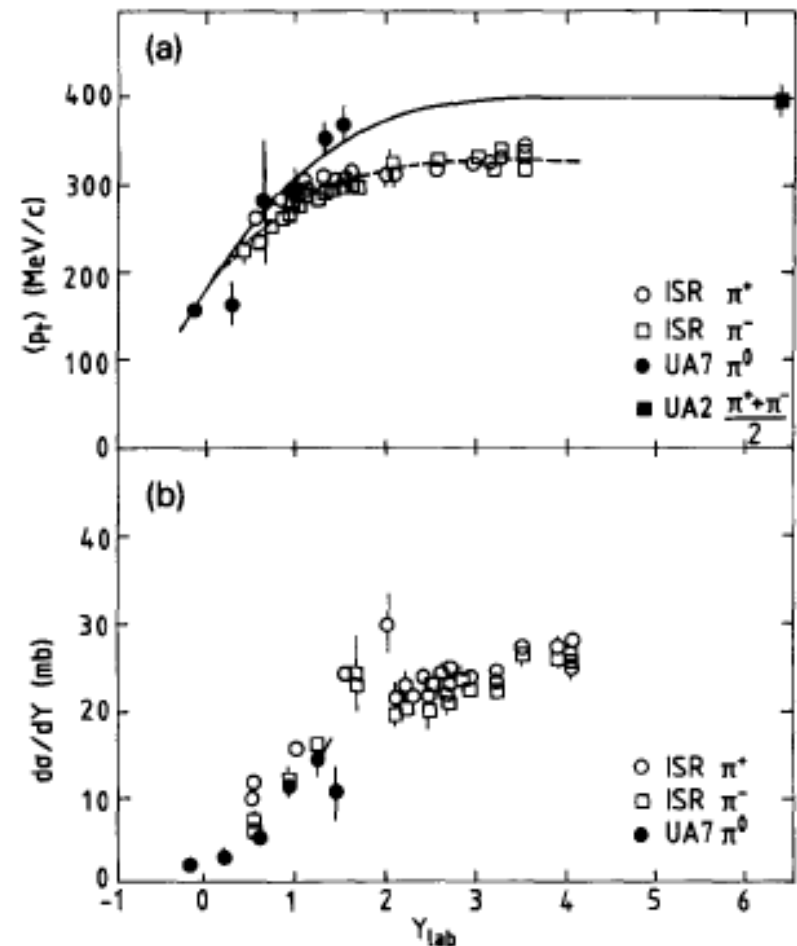
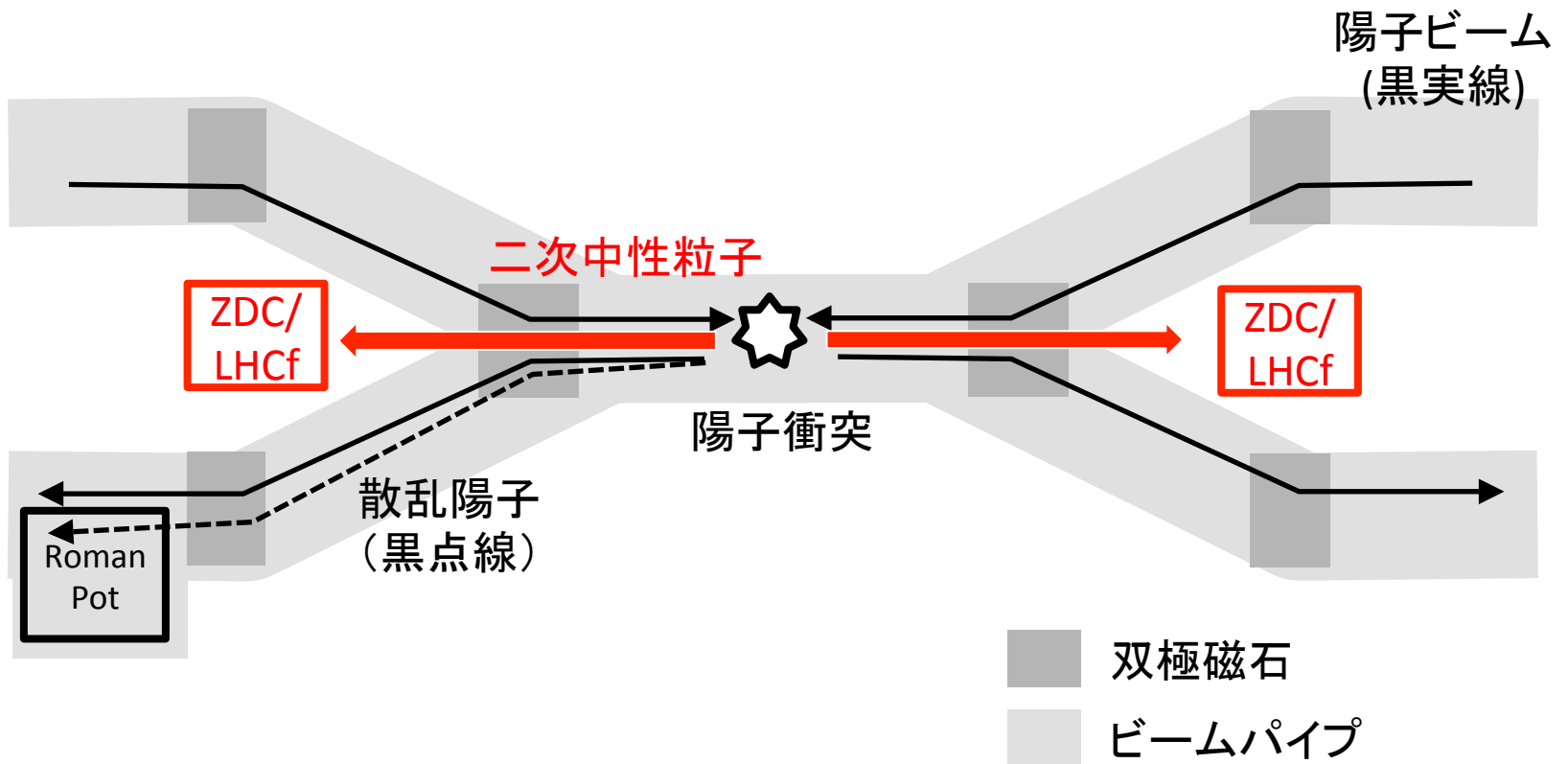


Fig. 4. (a) Average p_T of the π is given as a function of the rapid-

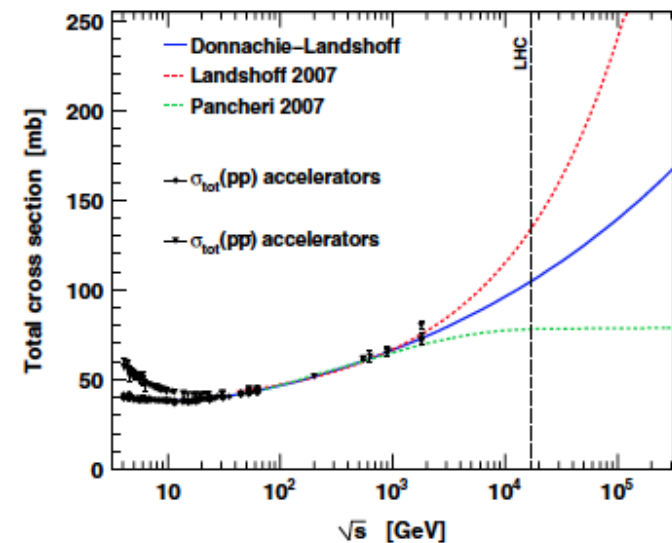
π^0 : UA7 Feynman scalingを破らない

超前方の測定原理



全断面積不定性と $X_{\max}$ への影響

(R.Ulrich, PRD, 83 (2011) 054026)



$$f(E, f_{19}) = 1 + (f_{19} - 1)F(E),$$

$$F(E) = \begin{cases} 0 & E \leq 1 \text{ PeV} \\ \frac{\log_{10}(E/1 \text{ PeV})}{\log_{10}(10 \text{ EeV}/1 \text{ PeV})} & E > 1 \text{ PeV} \end{cases}$$

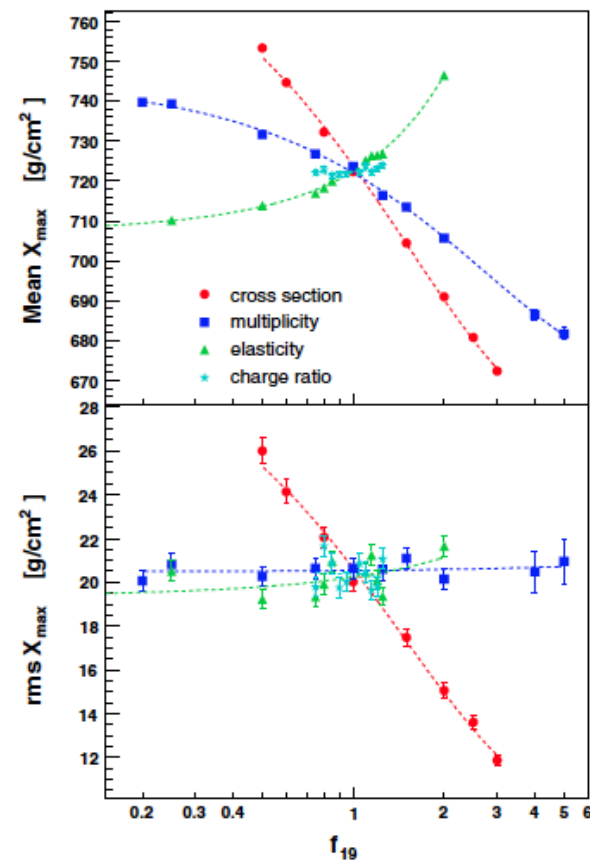
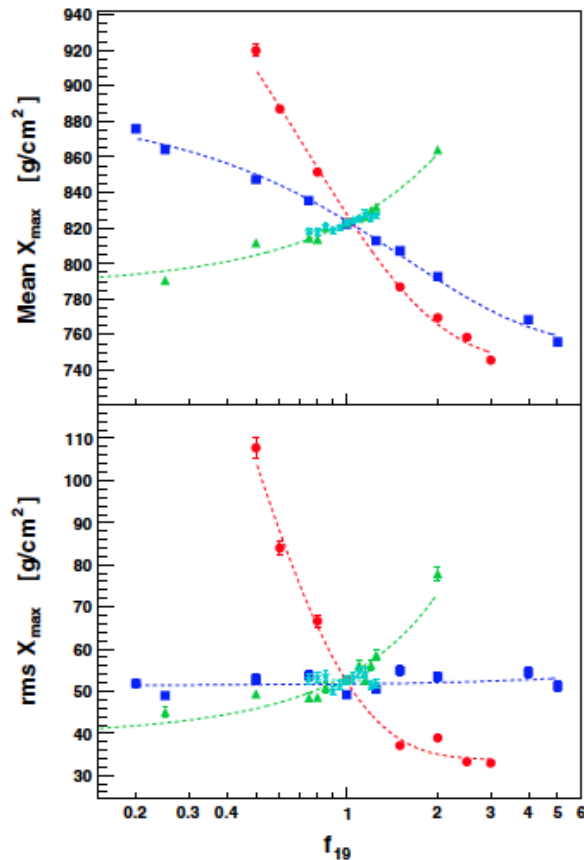


FIG. 7 (color online). Impact of hadronic interaction features on the shower maximum, $X_{\max}$, for proton (left) and iron (right) primaries.