

高エネルギーハドロン衝突の QCD物理

2017年 12月 5-7日

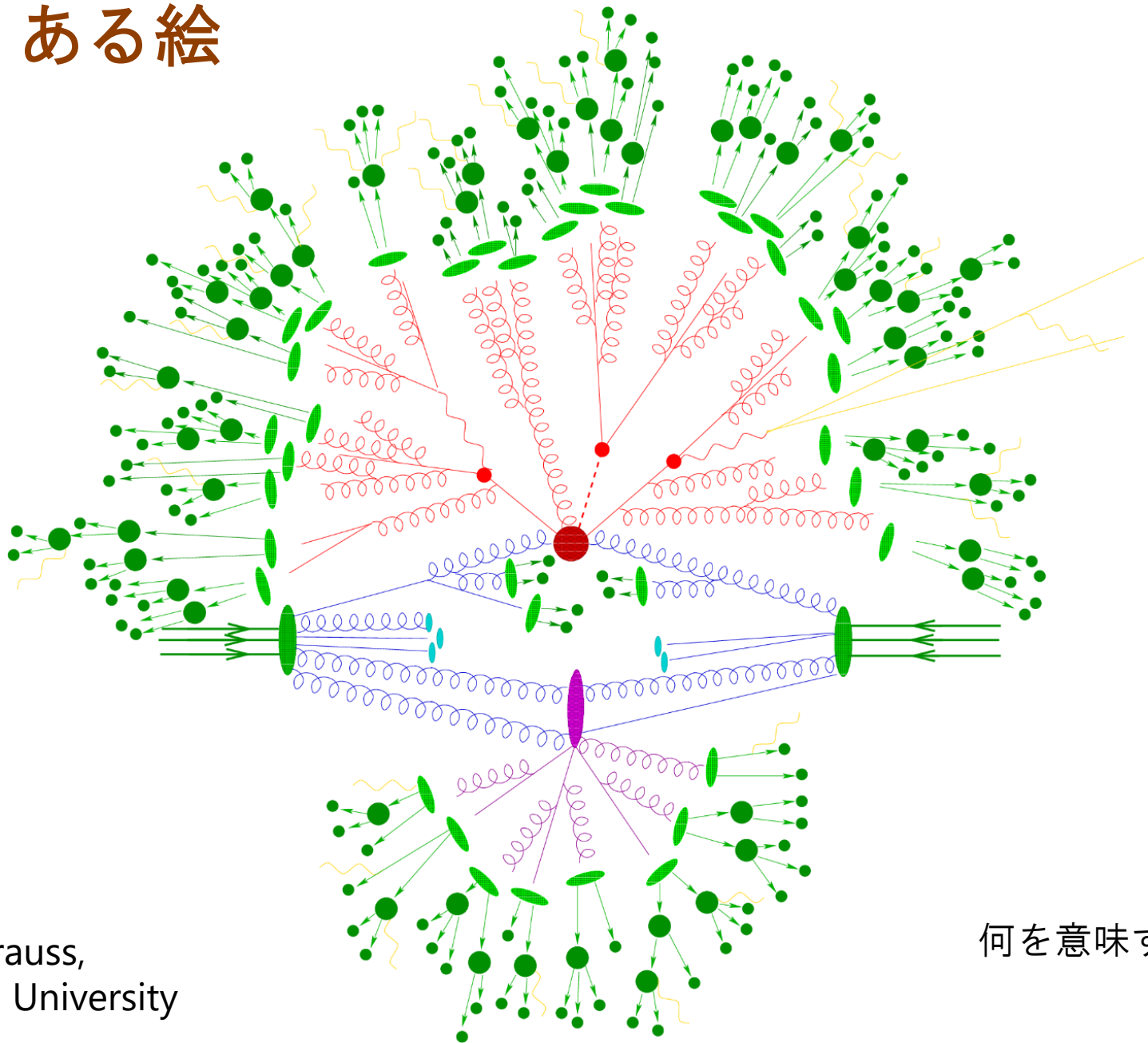
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講義の内容

1. ハドロン散乱の基礎過程
ソフトな散乱とハードな散乱，様々なプロセス
2. パarton密度
フォーマリズム，電子・陽子散乱による測定，解釈
3. ハードな散乱と摂動論的QCD
ジェットと破砕化，高次の摂動計算入門， α_s 測定
4. 談話会：「LHC 陽子散乱の理解と QCD:
トッブクオーク，新物理探索を例にとって」
5. ソフトな散乱
全断面積，回折散乱，多重parton散乱
6. 回折散乱の摂動論的理解と前方の物理
回折散乱の実験・解析手法，前方粒子生成

よくある絵

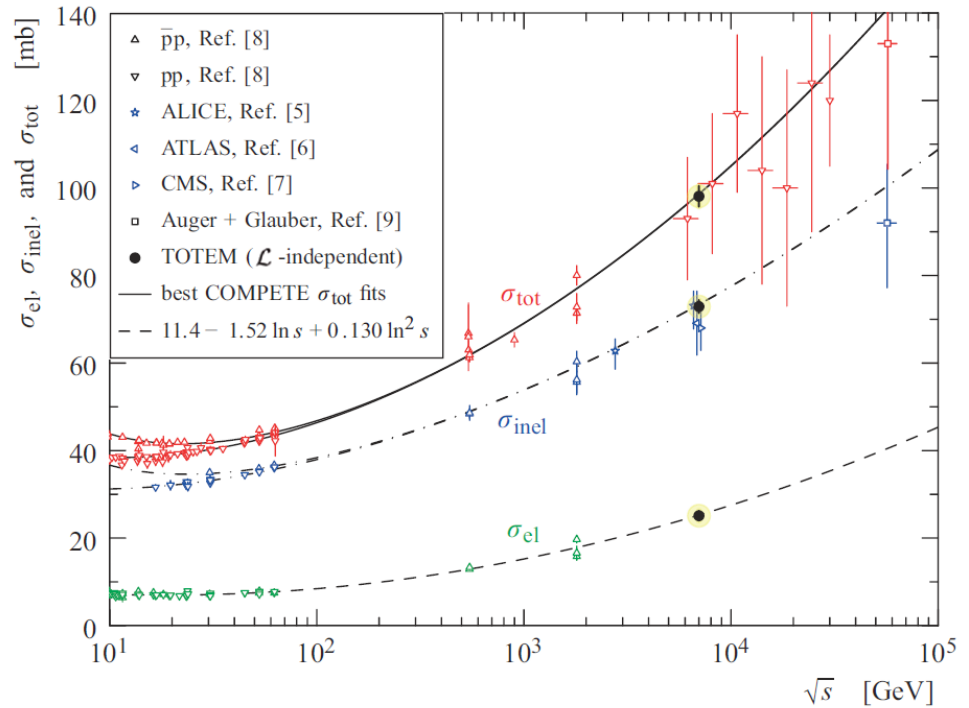


Frank Krauss,
Durham University

何を意味する？

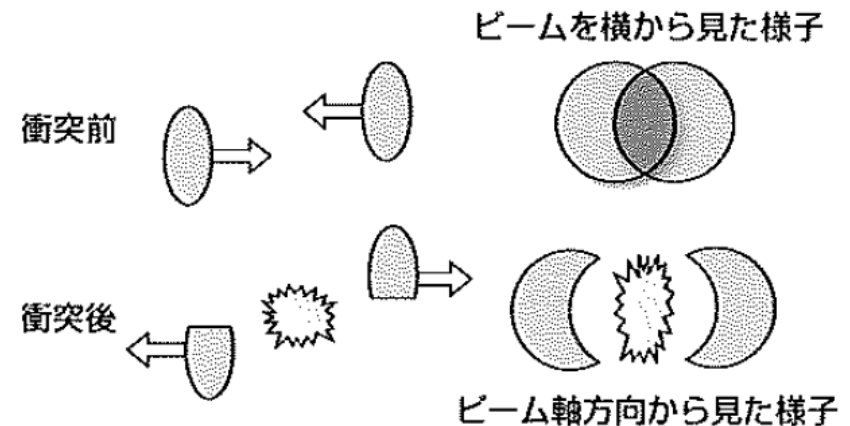
pp total cross sections

- \sqrt{s} の緩やかな関数
 - 4桁の範囲に及ぶと思うと、
ほぼ一定と言ってよい
- これは、素粒子の散乱ではありえない
 - e.g. $e^+e^- \rightarrow \mu^+\mu^-$
(s-channel)
$$\sigma(\sqrt{s}) = \frac{4\pi\alpha}{3s}$$
 - t/u-channel でも似た感じ
 $1/E^2$ に比例
(次元からも, $\sigma \propto L^2 \propto 1/p^2$)
- なぜ？



Soft hadron = quark matter, not partons

- この σ_{tot} がほぼ一定なことは、定性的には以下のように理解
 - 入射陽子はクォーク物質 (quark matter)
= クォーク, グルーオン, でできていて,
パンケーキ状態になっている
 - 非摂動状態で「たくさん」の parton が
高密度の状態になっている
 - 強い力なので, 短距離力
(湯川相互作用) cf. クーロン力
ぶつかる確率は, よい近似で
 - 断面のオーバーラップあれば 1
 - 離れていれば, ぶつからない
 - ならば, 第1近似で断面積は
エネルギーに依らない
ぶつかる入射ハドロンのサイズにのみ依る
($\sim 1 \text{ fm}^2 = 10 \text{ mb}$)



中間子交換による相互作用の記述

- パイオンなどを交換粒子として，弾性散乱は場の理論で計算できる

- 全段面積は，Optical Theorem（光学定理）で

- この証明は，量子力学で

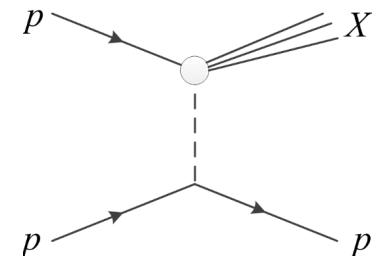
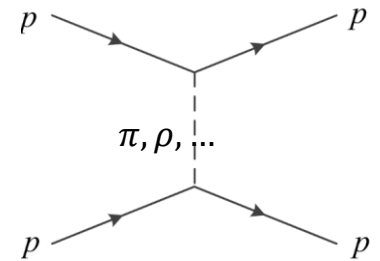
- 絵的には

$$\left| \text{Diagram} \right|^2 = 2 \text{Im} \text{Diagram}$$

- 「回折散乱」も，この手法で記述できる

- 細かくはあとで

いわゆる，レッジエ (Regge) 理論



パイオン交換で説明できるか

- (量子数さえ合っていれば) パイオン交換が相互作用のおもな寄与
- 湯川ポテンシャル

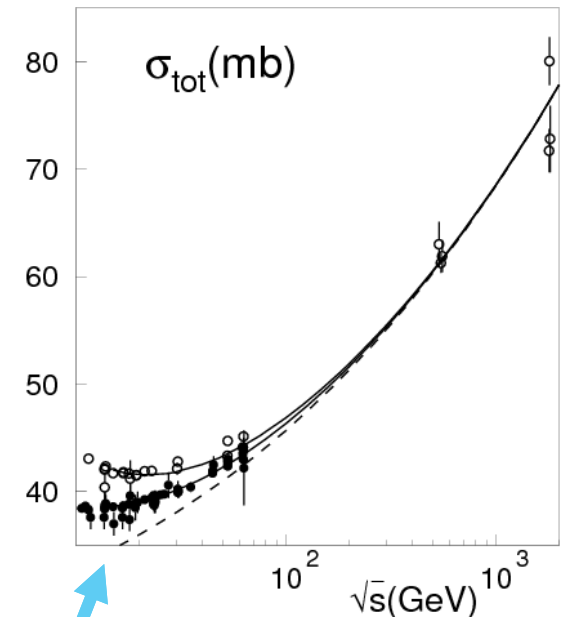
$$V(r) = -\frac{g^2}{4\pi} \frac{e^{-m_\pi r}}{r}$$

- 短距離力ではあるが, 力積の有効距離を考えると, やはりエネルギーによる

$$\sigma \sim \frac{|A|}{p^2}$$

- 実際, 中間子交換では断面積は $1/s^{(\alpha-1)}$ のように減少
 - 量子数から ρ meson とその励起状態が主
 $\alpha_\rho \sim 0.5$ より $\sigma(\rho \text{ exch.}) \propto 1/\sqrt{s}$
- 一定ではない
 - 測定は, 散乱振幅が $|A| \propto s^\alpha$ ($\alpha \sim 1$)
 - ハドロン散乱の長年の疑問

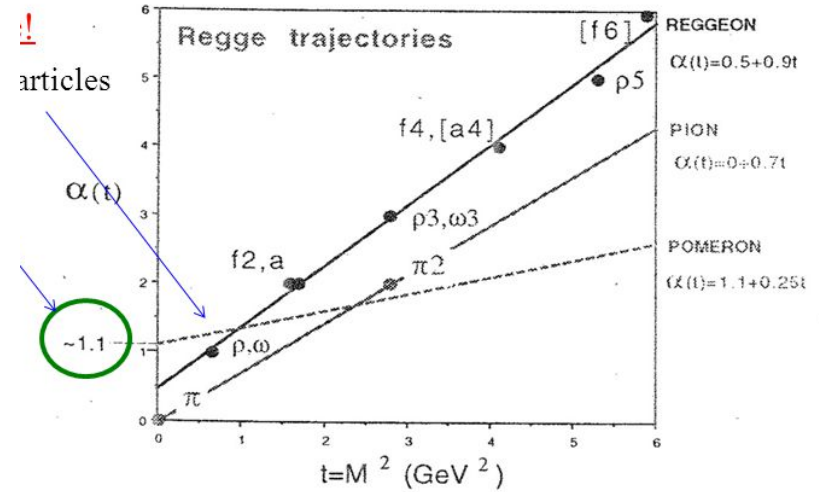
Kopeliovich, B.Z. et al. Braz.J.Phys. 37 (2007) 473-483



Meson contribution:
difference between
solid and dashed lines

The Pomeron

- ロシアの理論家 Pommeranchuk 由来
- 仮想的な複合粒子で，断面積を説明するために導入

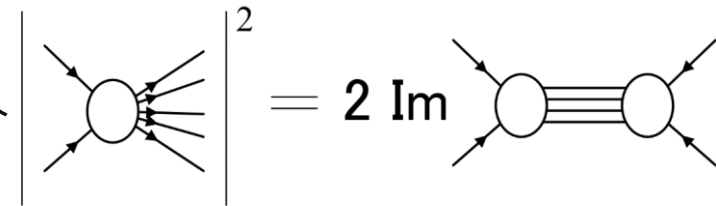


– Regge 理論で弾性散乱は

$$\frac{d\sigma_{el}}{dt} \sim \frac{1}{s^2} |A|^2 \sim \left(\frac{s}{s_0}\right)^{2\alpha(t)-2}$$

: $t \sim -p_T^2$ (recoil proton) 弾性散乱の場合

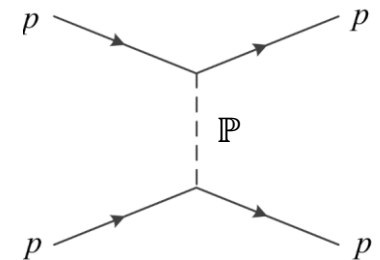
$\alpha(t)$: Regge trajectory



– 全散乱断面積（光学定理）

$$\sigma_{tot}^2 \approx 16\pi \left. \frac{d\sigma_{el}}{dt} \right|_{t=0} \rightarrow \sigma_{tot}(s) = \sigma_0 \left(\frac{s}{s_0}\right)^{\alpha_0-1}$$

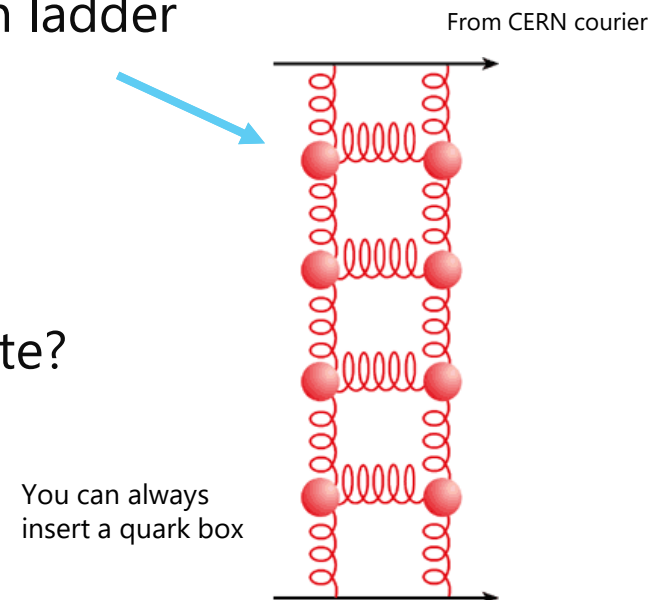
– $\alpha(t) = \alpha_0 - \alpha' t = 1 + \epsilon - \alpha' t$: "Pomeron trajectory"
直線近似で $\alpha_0: \sim 1.08$, $\alpha' \sim 0.25 \text{ GeV}^{-2}$



- "the cross section behaviour is explained by Pomeron exchange (or by Pomeron trajectory)" とか言う

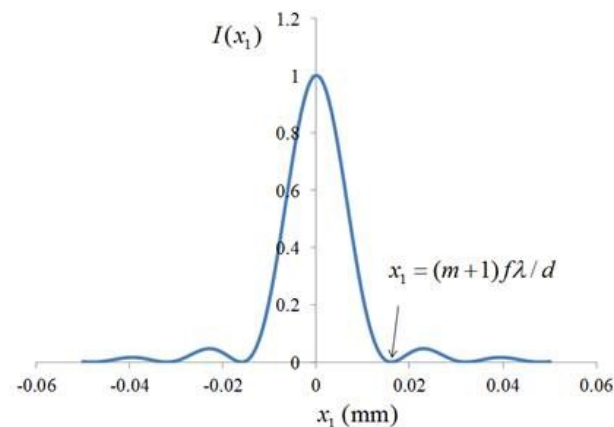
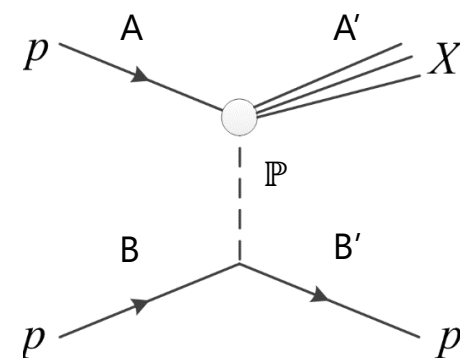
What is Pomeron, guys?

- It is a light meson-like object
 - but we know that the lightest mesons are not Pomeron
- Most likely: it is a “dressed” gluon
 - Lowest colourless gluonic object: 2-gluon state
 - Strongly interacting → becoming a gluon ladder i.e. not 100% gluonic object
- Questions:
 - Is it a particle, or just an intermediate state?
 - Partonic contents of the object?



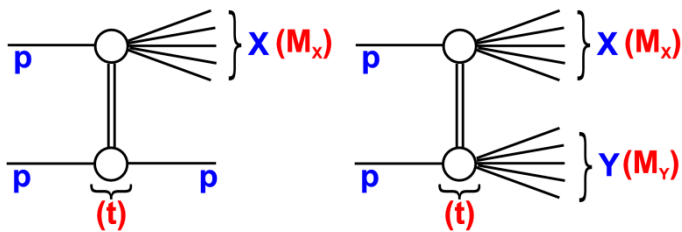
Diffraction scattering

- 弾性散乱では, proton A, B の間にカラー交換はない
- A', B', などのように, multi-hadronic state に変化 (dissociate) することがある。 $m_{A'}, m_{B'}$ は小さめ
- これは, 光学における回折とよく似ている
 - 空間分布は変わるが, 量子数は変わらない
- であれば, 交換粒子はカラーを持たない
 - それが高エネルギーでは "Pomeron" のせい, あるいはそれに似た粒子のせいと考える

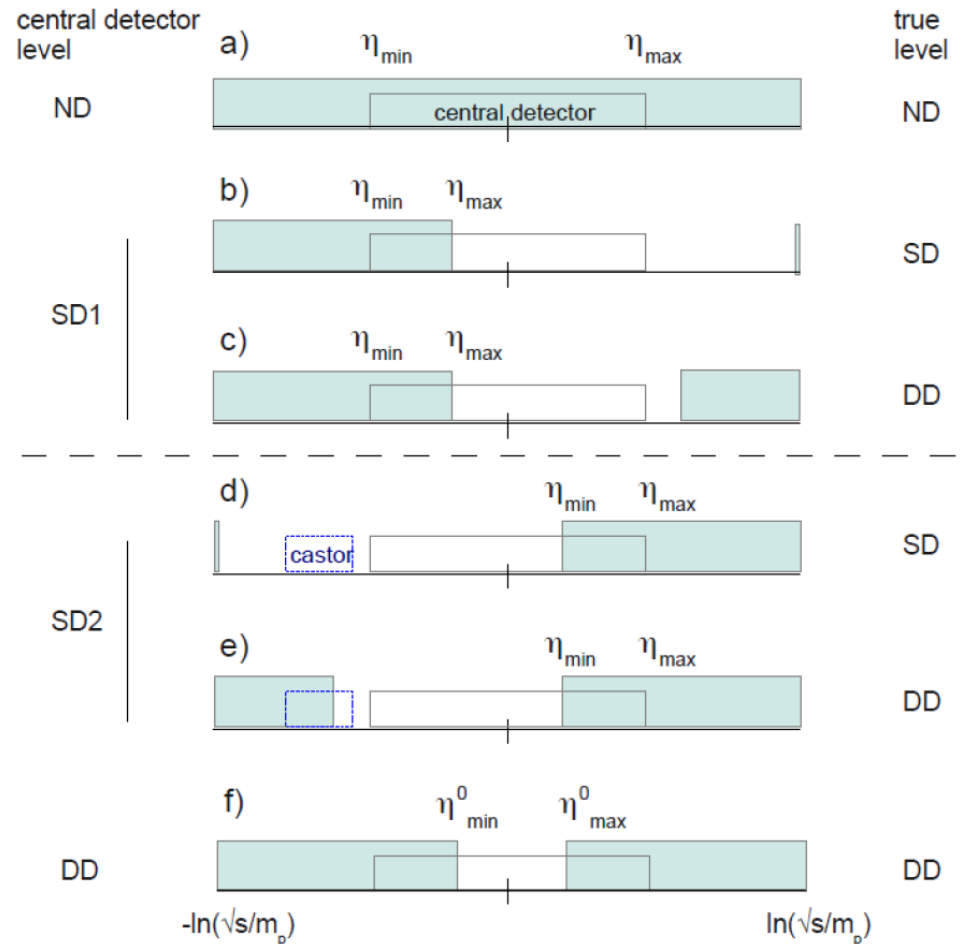


Signal of diffraction in pp collisions

- Observation of collimated hadrons (or a proton), system A' and B' , in very forward direction
- Large Rapidity Gap (LRG) between the system A' and B'

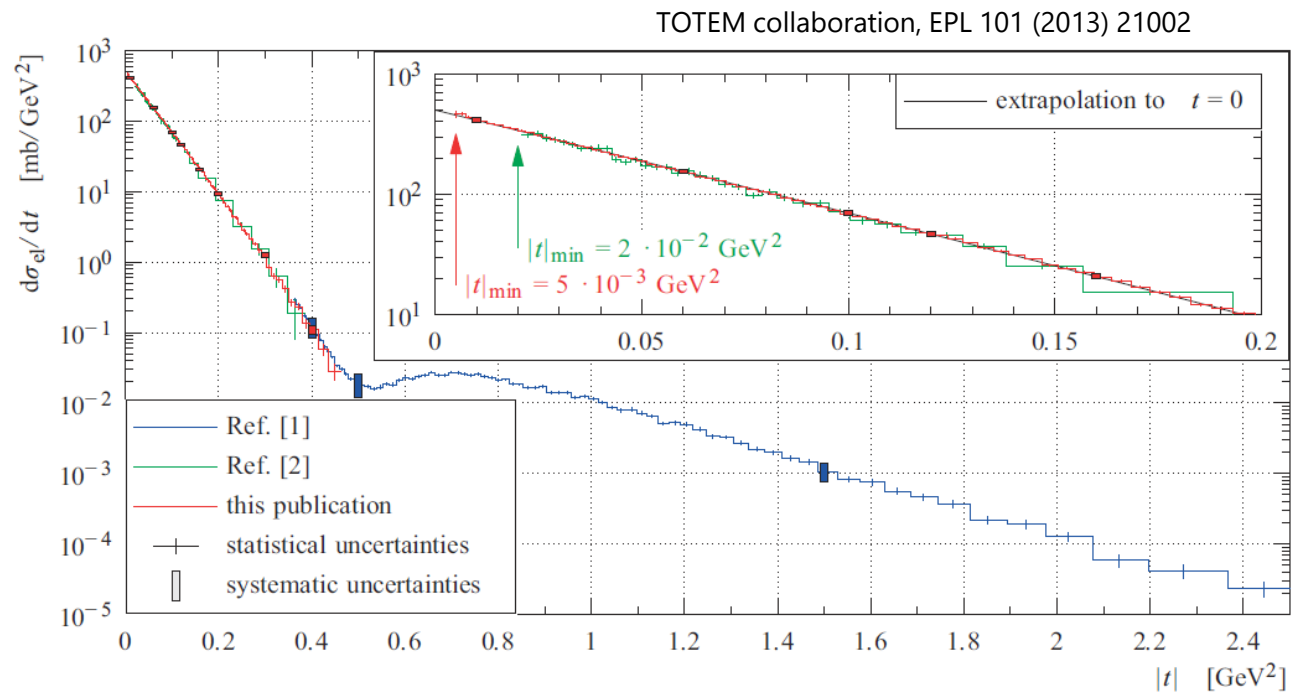


Single diffraction Double diffraction



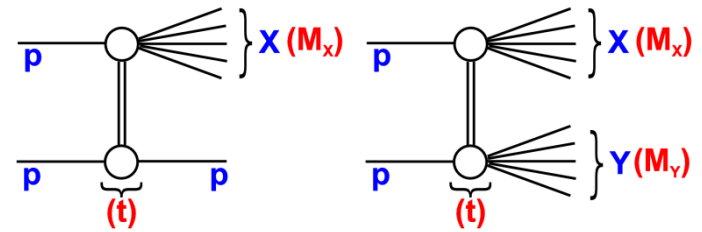
Scattering angle of elastic/diffractive proton

- You see diffractive peak and also dip

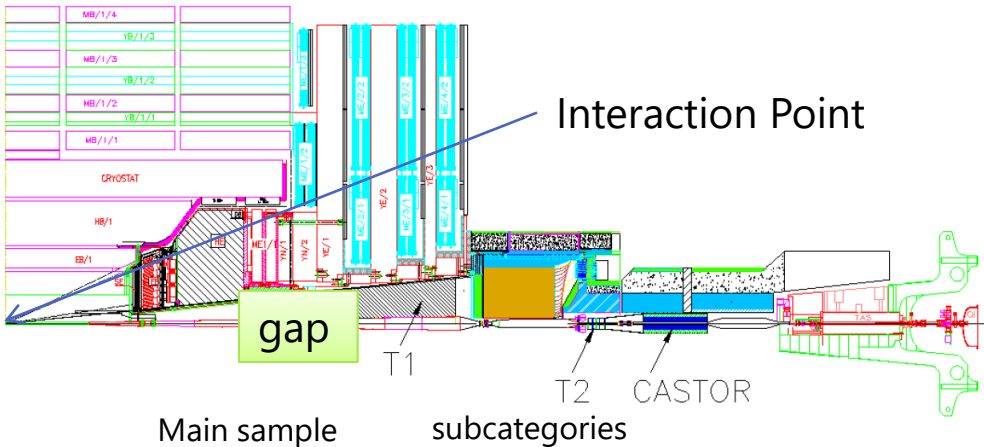


Double diffraction by TOTEM

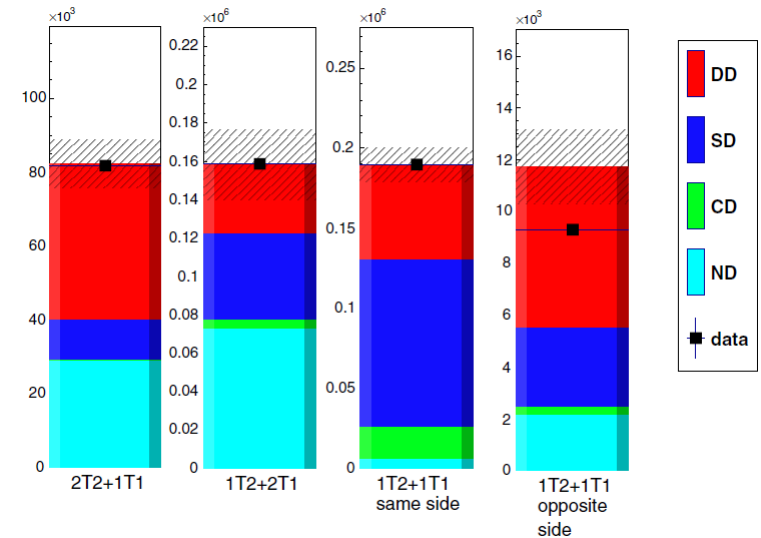
- T1 and T2 telescopes to tag proton dissociation system
 - T2 to tag the system X/Y
 - T1 veto for rapidity gap



Single diffraction Double diffraction



	I_{track}	$D11_{\text{track}}$	$D22_{\text{track}}$	$D12_{\text{track}}$	$D21_{\text{track}}$
Visible	131 ± 22	58 ± 14	20 ± 8	31 ± 5	34 ± 5
in μb					
η_{min}	116 ± 25	65 ± 20	12 ± 5	26 ± 5	27 ± 5
PYTHIA η_{min}	159	70	17	36	36
PHOJET η_{min}	101	44	12	23	23



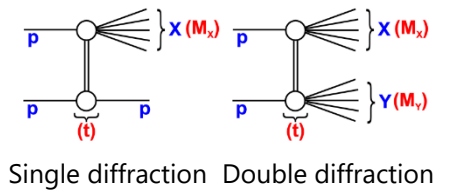
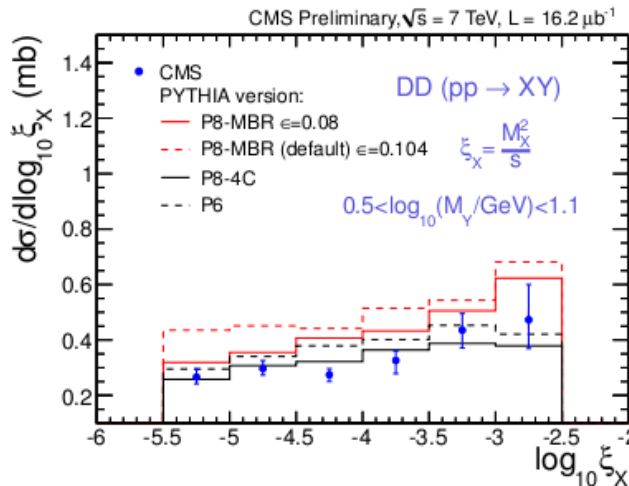
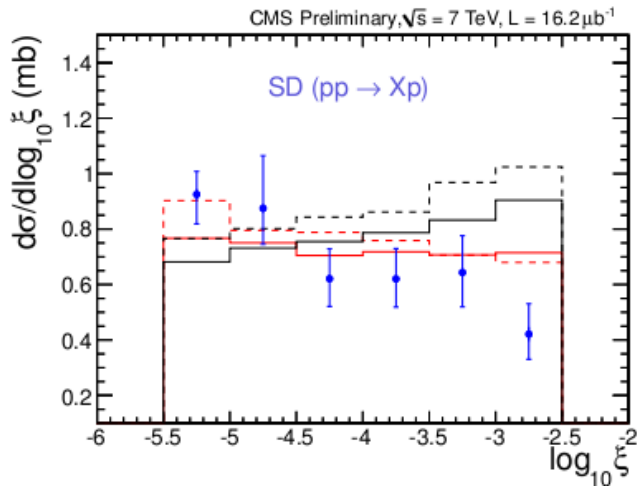
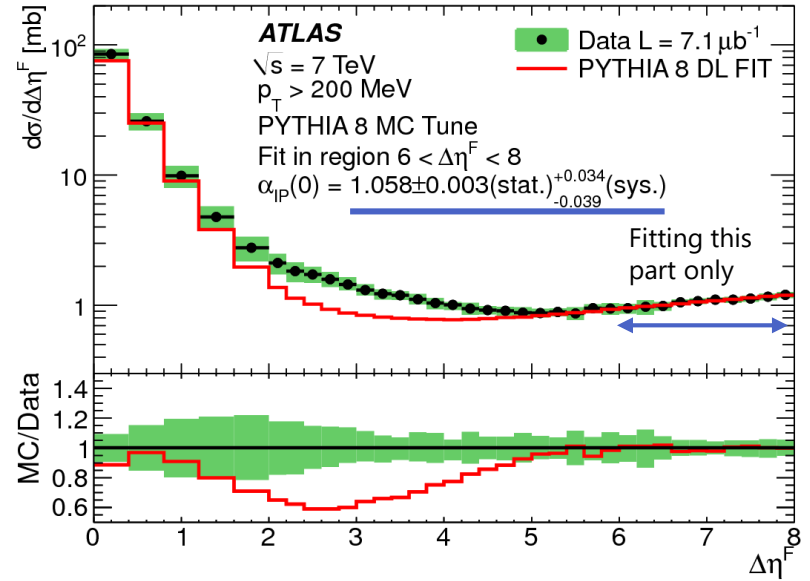
Somewhere between two models
Next: t-dependence

Events with LRG: ATLAS and CMS

- α_0 extracted from cross section dependence with rapidity gap $\Delta\eta$
 - triple-Pomeron formula:

$$\frac{d\sigma}{d\xi_X} \propto s^{-1+\epsilon} \xi_X^{-(1+\epsilon+2\alpha't)}$$

$$\xi_X = \frac{M_X^2}{s}$$
 (longitudinal momentum fraction of the diffractive exchange)
 - $\Delta\eta \simeq -\ln \xi_X$
 \rightarrow cross section rise by $\sim (\Delta\eta)^\epsilon$
 - DL universal Pomeron: $\alpha(0) = 1.08$

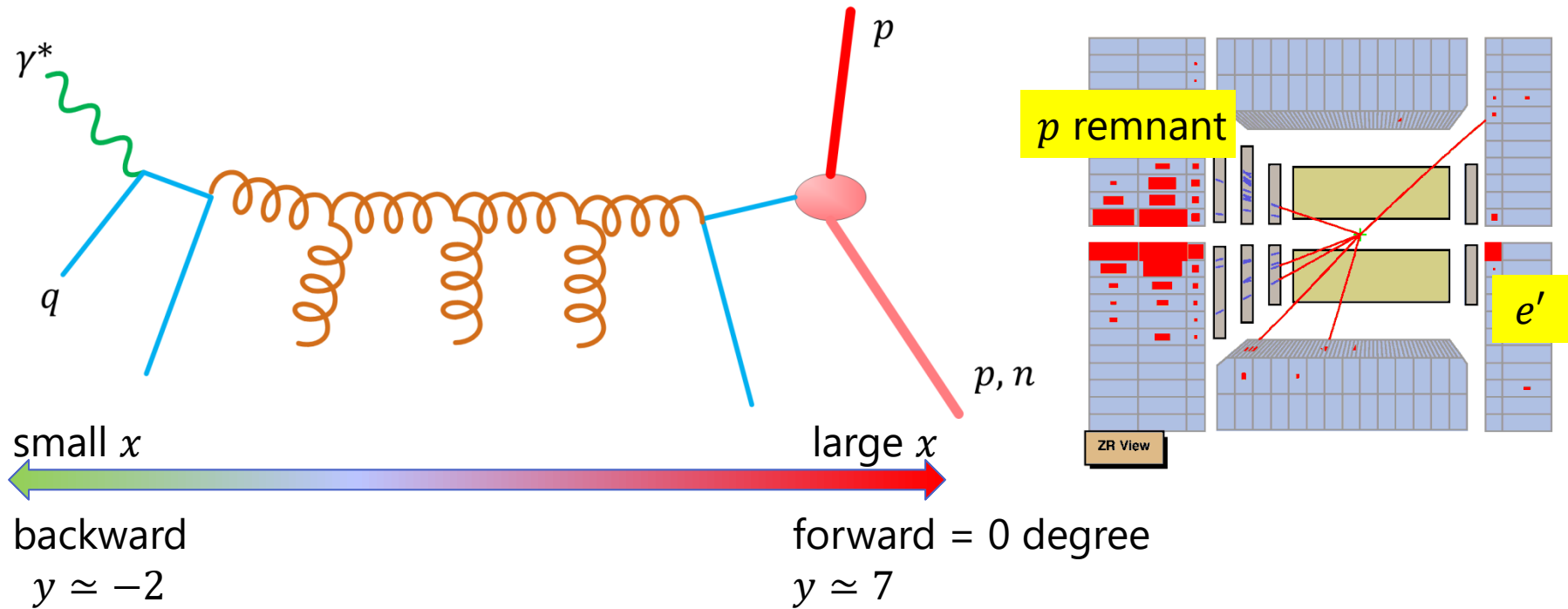


MBR: Rockfeller saturation model
 on top of universal Pomeron
 P8, P6: Schuler-Sjostrand Pomeron with partonic structure

様々な soft QCD process

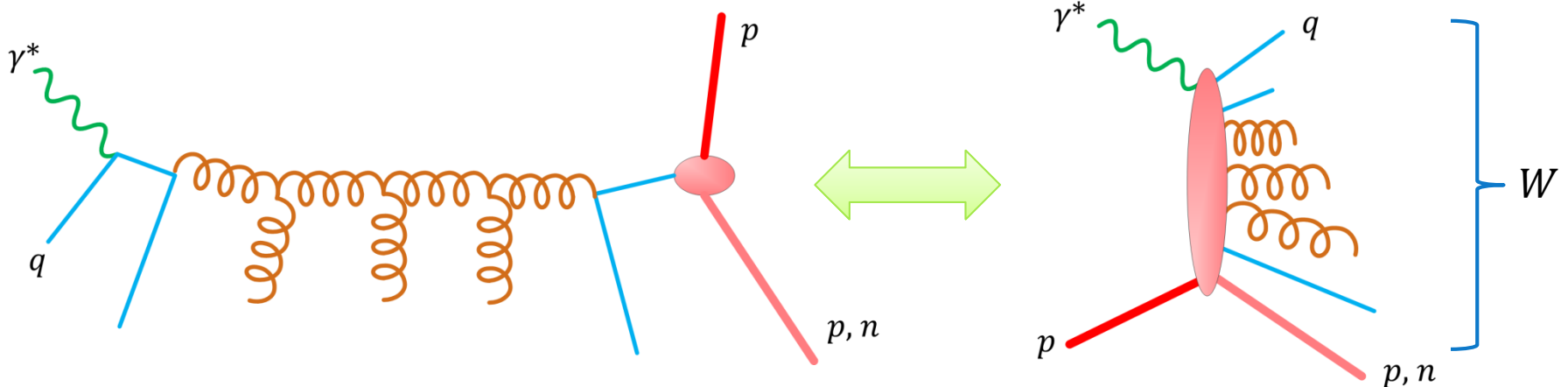
- 回折散乱では前方に粒子が出て，LRG があり，後方にも粒子が出る
- 一般の非弾性散乱では LRG はないが，前方に粒子が出る
- 前方に早い粒子が出るということは，ほとんど運動量を失っていない（横，縦ともに）
 - 散乱した粒子は low- x (parton or Pomeron)
- 電子・陽子散乱は，（仮想）光子・陽子散乱とみなせる
これを使って説明

運動学の話：Low- $x \simeq$ forward



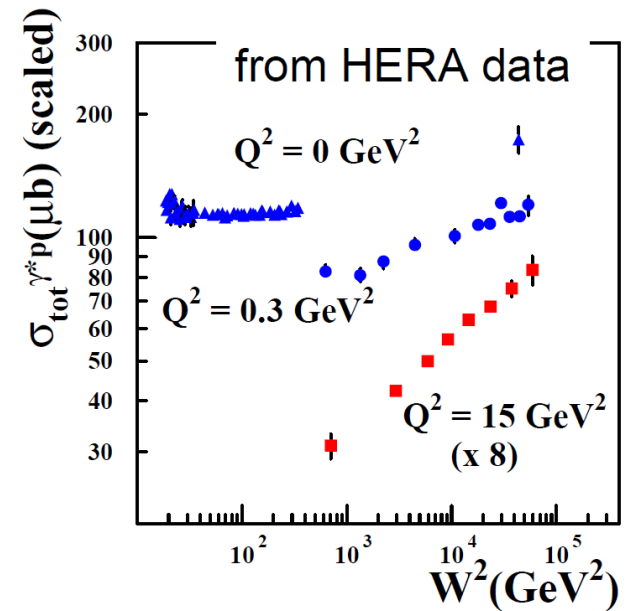
- small- x parton を陽子から取り去っても，陽子の運動量はほとんど変わらないで前方に飛ぶ
- Small- x parton は “backward” 後方に飛ぶ
 - 前方粒子，後方粒子の間の large rapidity interval がある

ep at low- x is γ^*p scattering

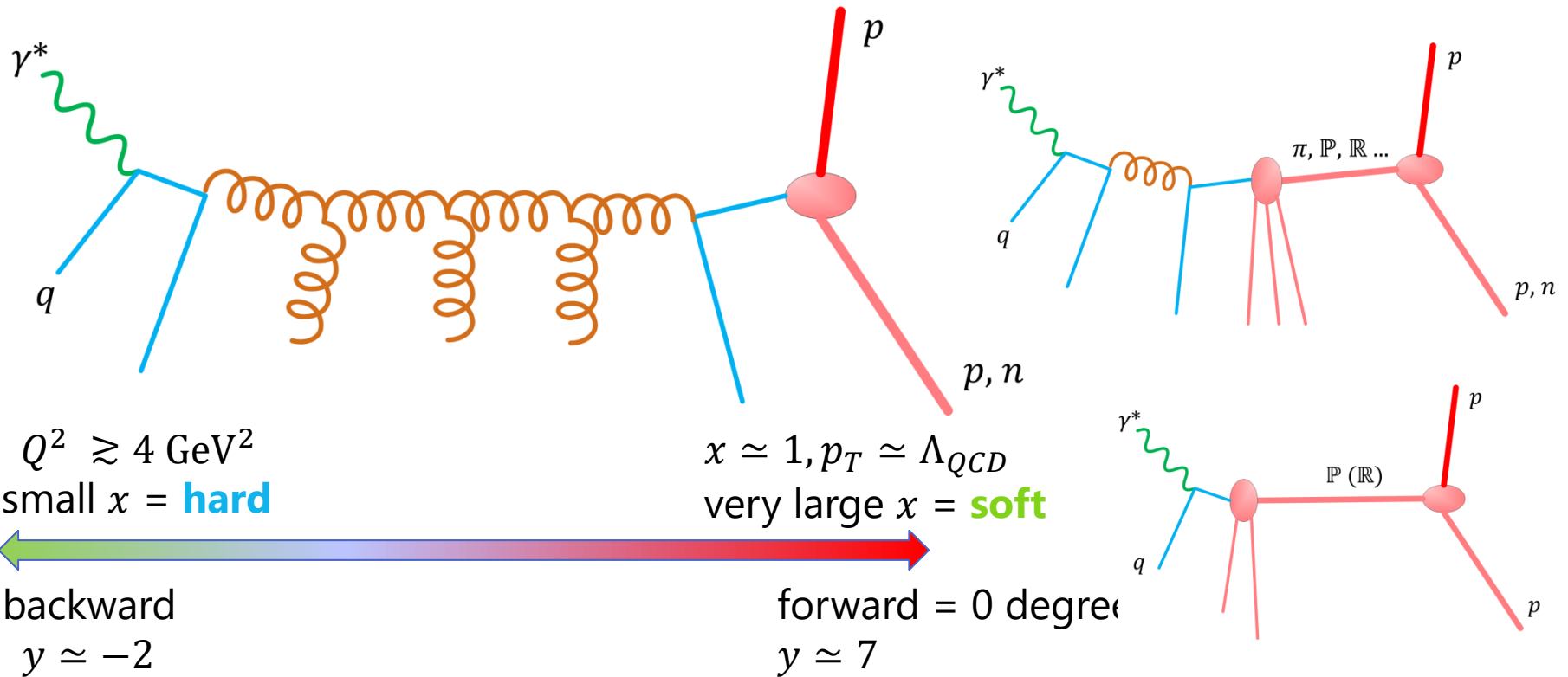


- low- $x \simeq \text{low-}Q^2$, 光子はハドロンと見なせる
- γ^*p centre-of-mass energy W は lower- x で大きくなる

$$W^2 = \left(\frac{1}{x} - 1\right) Q^2 \approx \frac{Q^2}{x} \quad (x \ll 1)$$
 - low- x = larger rapidity interval
- 全断面積の増加のふるまいが photon Q^2 が大きくなるにつれどんどん早くなる。
 - 光子中のパートンが見えるようになる, つまり仮想光子は "hard" object



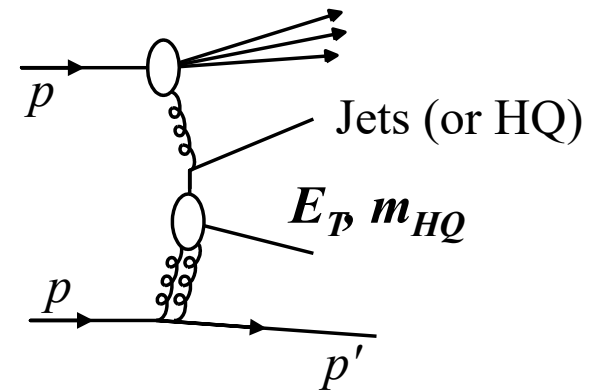
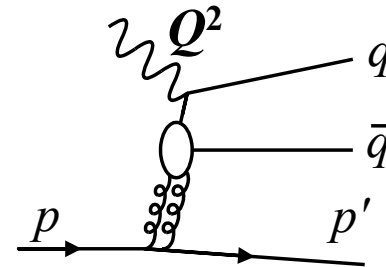
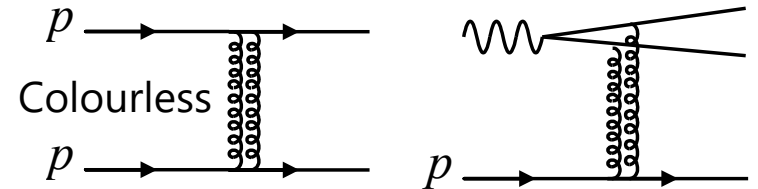
Soft or hard?



- Colourless particles appear more in forward (perhaps)
 - where is the transition, in which rapidity?

ep 散乱における回折過程とその意義

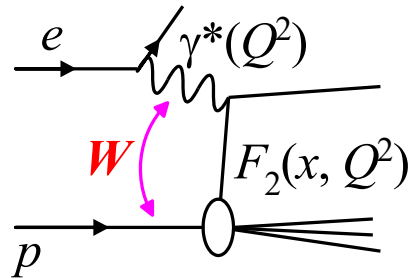
- ... is to understand the exchange in terms of pQCD
 - 2-gluon exchange at LO
 - The exchange itself does not have hard scale: typically $t \approx \Lambda_{\text{QCD}}^2$
Need a scale to see partons
- Probing partonic structure by **hard diffraction** e.g.
 - DIS, jet / HQ production, large t



The basic of hadron physics:

$W^2 \propto 1/x_{Bj}$ dependence

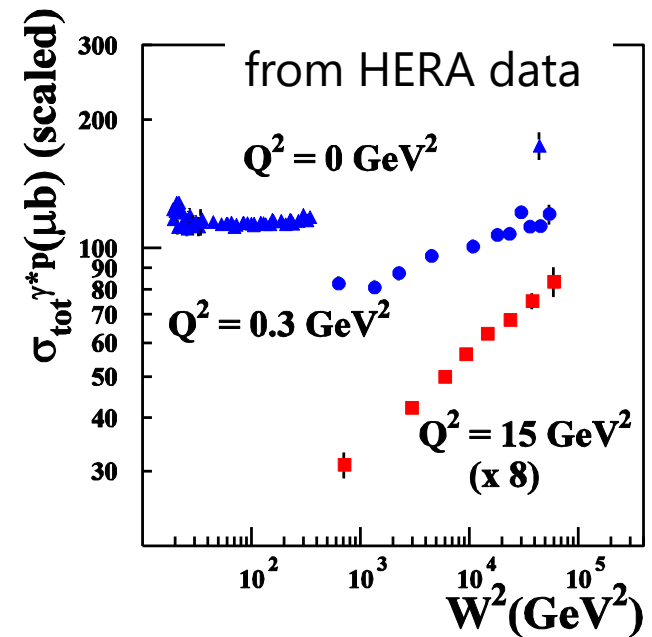
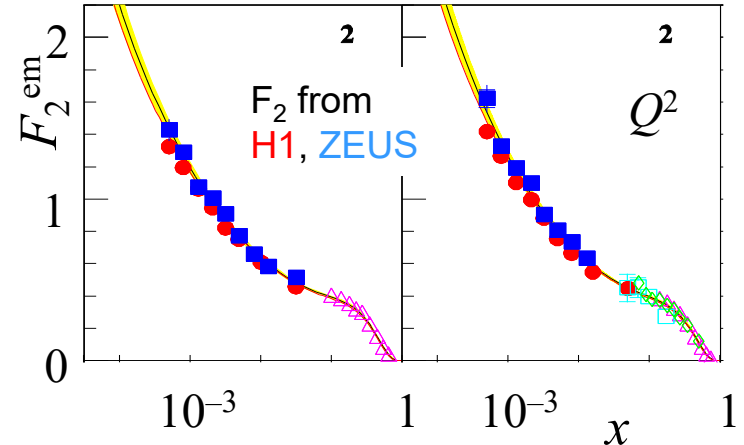
- F_2 rises steeply towards low- x_{Bj}



- This means: the cross section steeply rises with W , the centre-of-mass energy of $\gamma^{(*)}p$ system:

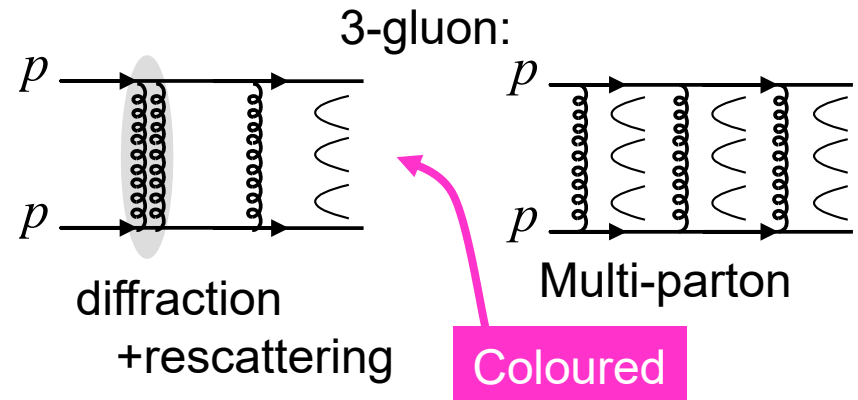
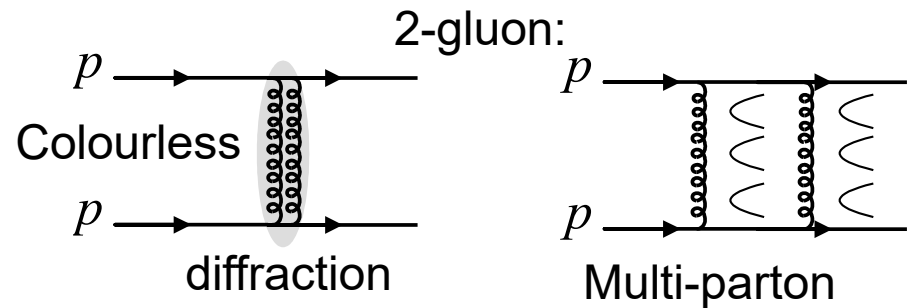
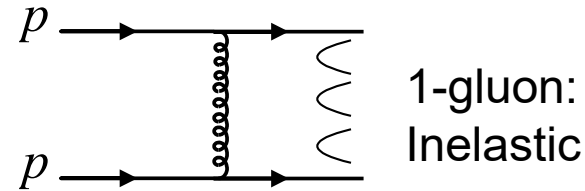
$$W^2 = \left(\frac{1}{x} - 1 \right) Q^2 \approx \frac{Q^2}{x} \quad (x \ll 1)$$

- Or: rise in s for hadron-hadron
- Fast rise in W : partons = pQCD
- Slow rise: soft collisions

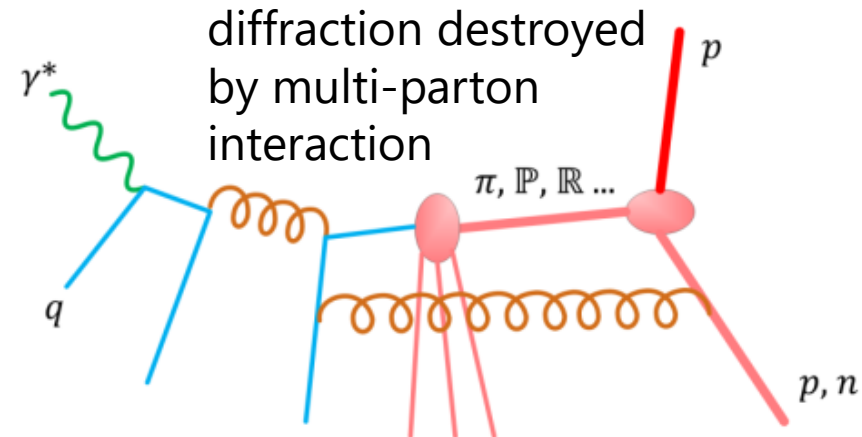
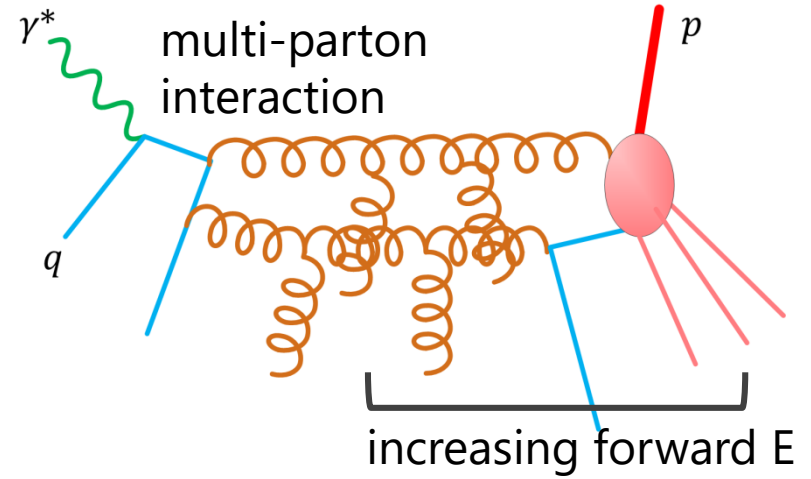
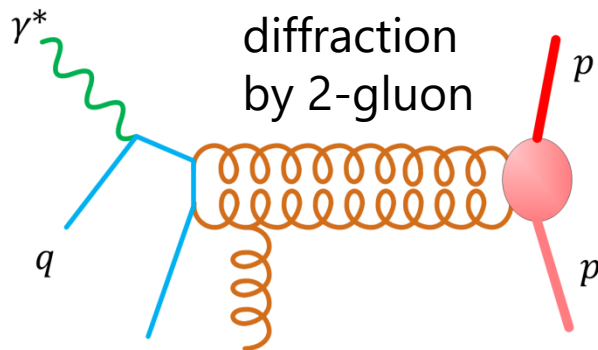
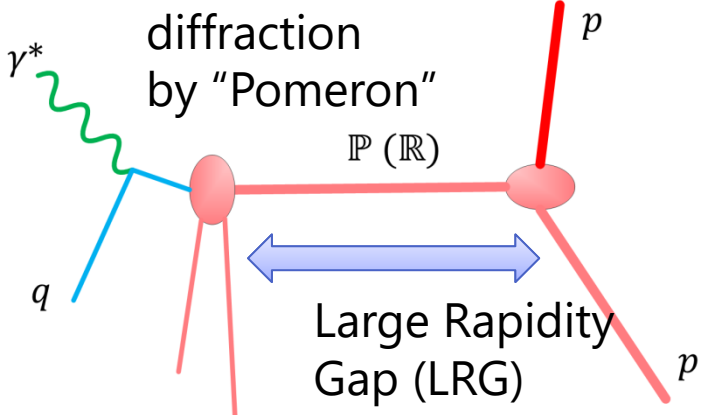
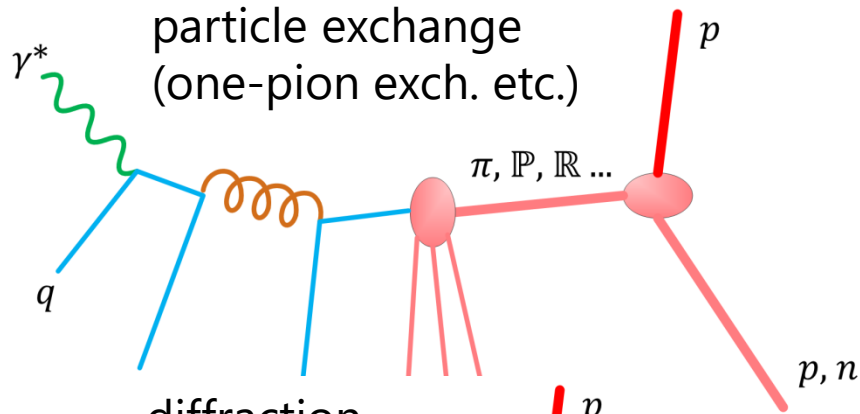


Why diffraction ? a simple view

- Plenty of partons at low- x
 - 1-parton exchange
 - Hard scattering
 - 2-parton exchange
 - Multi-parton scattering – incoherent
 - Diffraction – coherent
 - 3 or more could occur as well
- These phenomena should be explained uniformly
 - Cannot be ignored at high energy



partons \times phase space = various phenomena



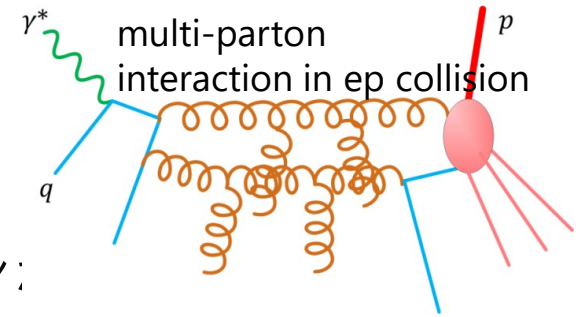
- where colourless,
where colourful?

Multi-parton interaction at the LHC

- high \sqrt{s} and low p_T では

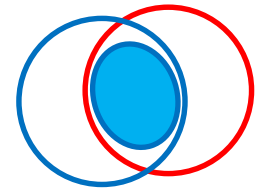
$$\sigma_{parton} > \sigma_{inelastic}$$

- 一回の陽子・陽子衝突で多数のパートンが散乱していることになる
- 過去 Tevatron で見え, HERA でも γp (real photon) で証拠が



- 多重散乱の cross section は以下のように書ける

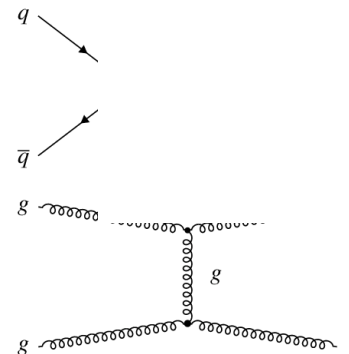
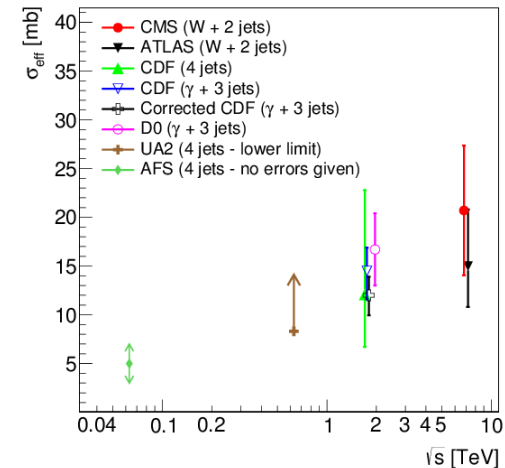
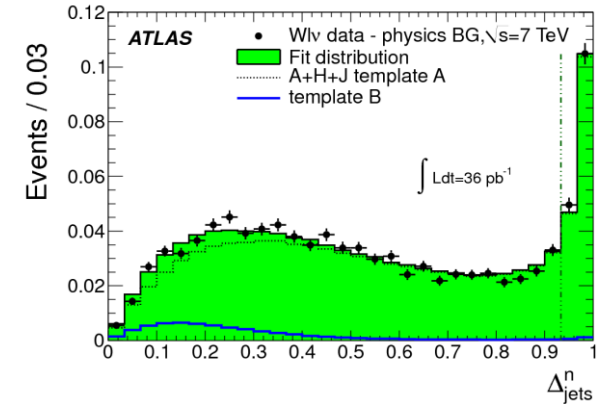
$$\sigma_{DPI}(A, B) = \frac{\sigma_A \cdot \sigma_B}{\sigma_{\text{eff}}}$$



- σ_A, σ_B : 2個の同時に起きる散乱が独立に起きたときのそれぞれの断面積 (\sqrt{s} とともに増加)
- σ_{eff} : 2つの入射粒子が重なっている 実効的 面積
 σ_{eff} 小さければビームが絞れていることになり σ_{DPI} が増す

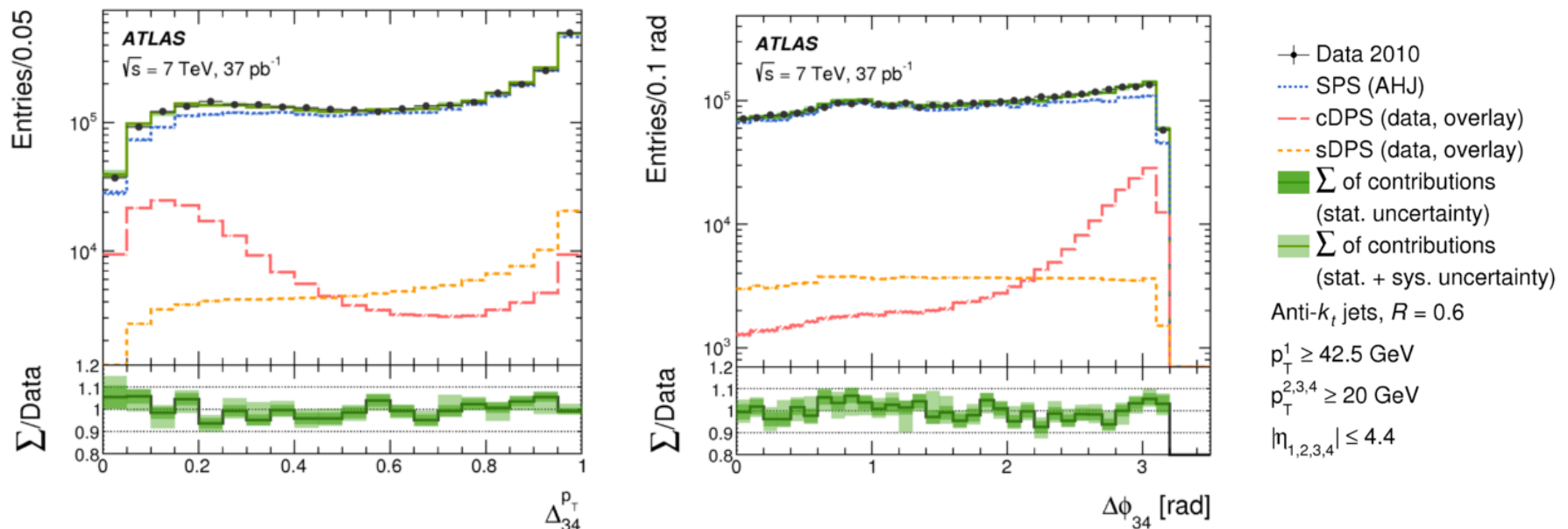
Multi-parton interaction and diffraction

- They are very closely related:
Both are based on multi-parton exchange
 - Diffraction: 2-gluon exchange, coherently in colour
 - MPI: colourless (colour-octet) exchange
- They occur more often at high-energy collisions
 - More partons at low- x , more chance to produce a state of a given mass
- Clear evidence at the LHC
 - Direct measurement by e.g. ATLAS
 - Minimum bias events can or be explained by models with MPI and colour reconnection



Double-parton interactions through 4-jets

- two types of double-parton scattering signal in 4-jet events
 - “cDPI”: complete-DPI, 2-jet \otimes 2-jet
 - “sDPI”: semi-DPI, 3-jet \otimes 1-jet
 - 1jet missing from detection for the “second” scattering
 - and generic 4-jet events from single parton-scattering



cDPI can be distinguished from the SPI, but sDPI not quite

Effective cross section σ_{eff}

- σ_{eff} : transverse area of the hadron causing DPI

– $\sigma_{4j}^{\text{DPS}} = \frac{1}{2} \frac{\sigma_{2j}^A \sigma_{2j}^B}{\sigma_{\text{eff}}}$, which can be obtained using the relation:

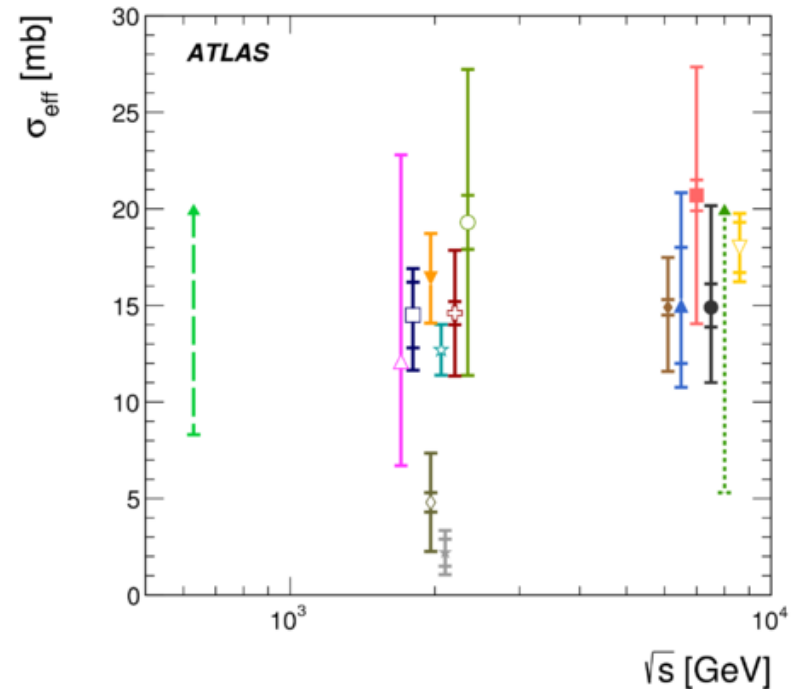
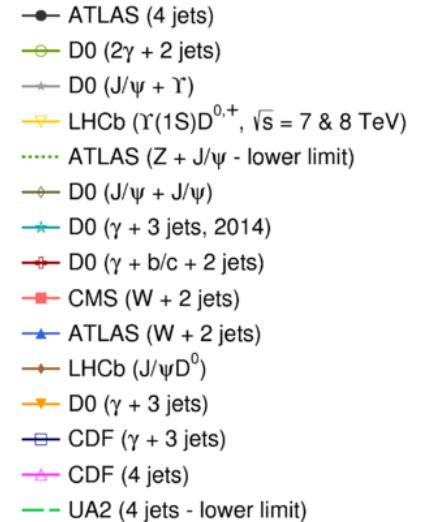
$\sigma_{4j}^{\text{DPS}} = f_{\text{DPS}} \cdot \sigma_{4j}$ and the dijet cross section σ_{2j}

- $\sigma_{\text{eff}} = 14.9_{-1.0}^{+1.2}(\text{stat.})_{-3.8}^{+5.1}(\text{syst.}) \text{ mb}$

- obtained from the measurement

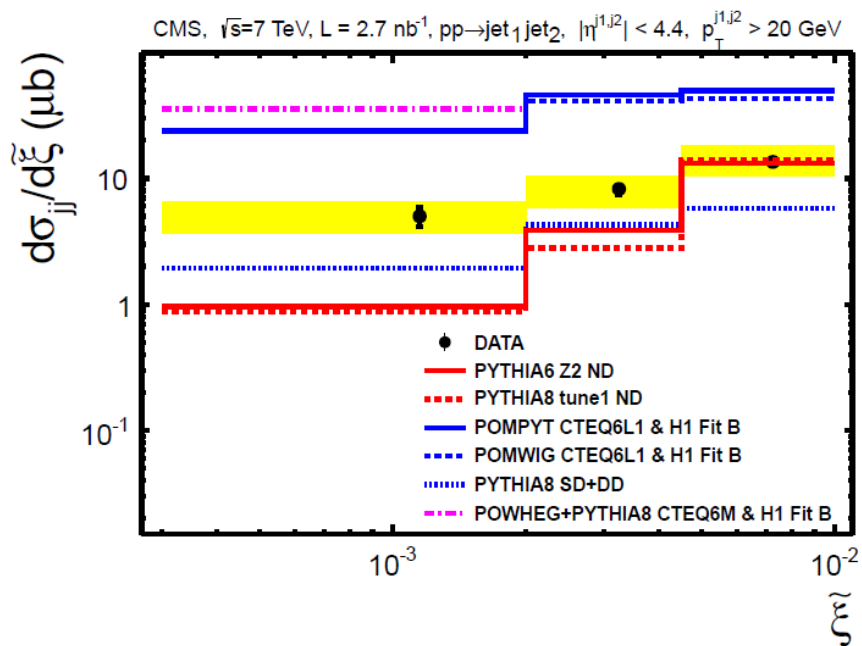
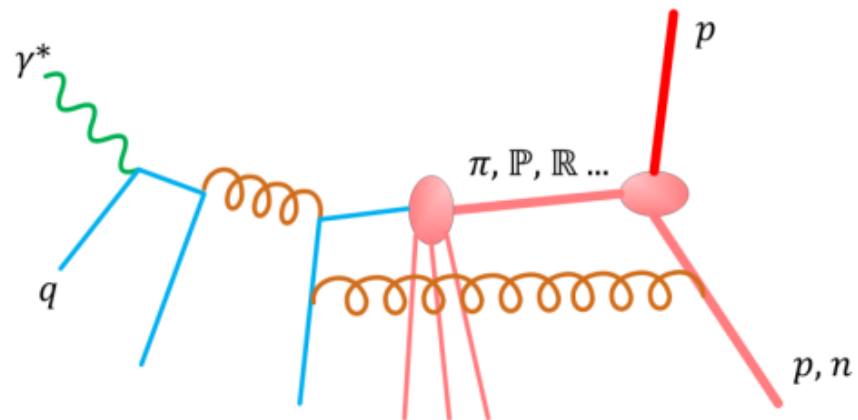
$f_{4j}^{\text{DPS}} = 0.092_{-0.011}^{+0.005}(\text{stat.})_{-0.037}^{+0.033}(\text{syst.})$

- No trend in increase/decrease as a function of \sqrt{s}



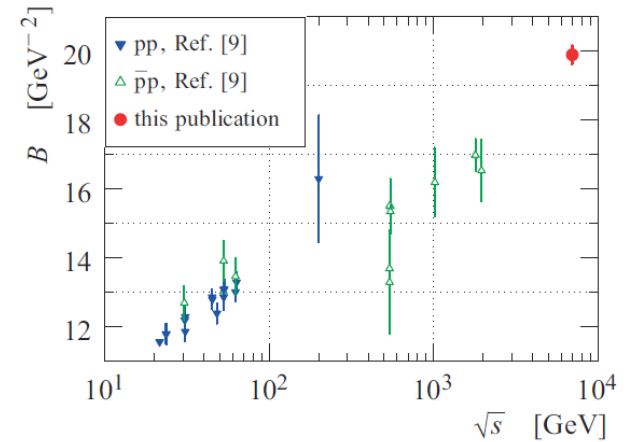
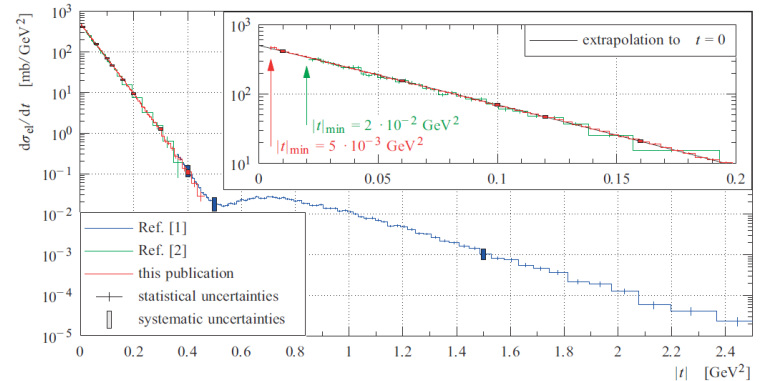
回折散乱の Gap survival probability

- 回折散乱に加えて parton(s) が交換されると, colour-singlet 状態が破壊される
- Tevatron では, 回折散乱は予想の 1/3-1/10 しか見られない
 - Pomeron flux (放出確率)
Pomeron parton densities (ポメロン構造関数) どちらも HERA 実験から求めたものを用いた場合
- LHC でも suppression as well
 - But not drastic suppression, only similar magnitude to Tevatron



なぜエネルギーとともに増加する？

- パンケーキモデルが正しいなら、パンケーキ、つまり入射粒子のサイズが大きくなっている
- 定量的には、高エネルギーでパートンが増えて、場所を食っている
- ただし、サイズが大きくなっている証拠はある（いわゆる Shrinkage）
 - 前方散乱のピークを $e^{-B|t|}$ でフィットしたとき、 B の値がエネルギーに伴って増える
 - ターゲットのサイズが大きくなっていることに相当



全散乱断面積の測定方法

- luminosity monitor を使う方法
 - 数を数えて見えないのを補正する方法
 - $\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2} \left(\frac{d\sigma_{el}}{dt} \right) \Big|_{t=0}$ より $t=0$ の断面積を extrapolate する方法
- luminosity 測定に依存しない方法 (Totem)

$$\sigma_{tot} = \frac{16\pi}{1 + \rho^2} \frac{\left(\frac{dN_{el}}{dt} \right) \Big|_{t=0}}{(N_{el} + N_{inel})}$$

$$\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2} \left(\frac{d\sigma_{el}}{dt} \right) \Big|_{t=0}, \quad N_{el} = \sigma_{el} \cdot \mathcal{L}_{int}, \quad N_{inel} = \sigma_{inel} \cdot \mathcal{L}_{int} \text{ より}$$

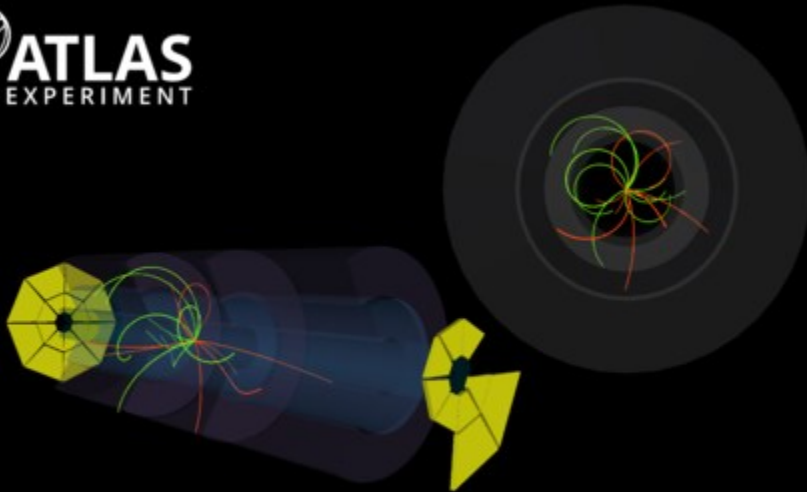
N_{inel} は diffraction を含んでおり、実験的にとらえられない low mass diffraction は補正 (Totem で 4%)

ρ は前方散乱振幅の虚部に対する実部の比 0.141 ± 0.007

Inelastic cross section @ 13 TeV

- MBTS (Minimum-bias trigger scintillators) を使って inelastic, SD (single-diffractive) and DD (double-) 事象をタグ
 - 角度領域 $2.07 < |\eta| < 3.86$, $\xi = M_X/s > 5 \times 10^{-6}$ に対応
- LHCf 含む他の検出器で MBTS のタグ効率を較正

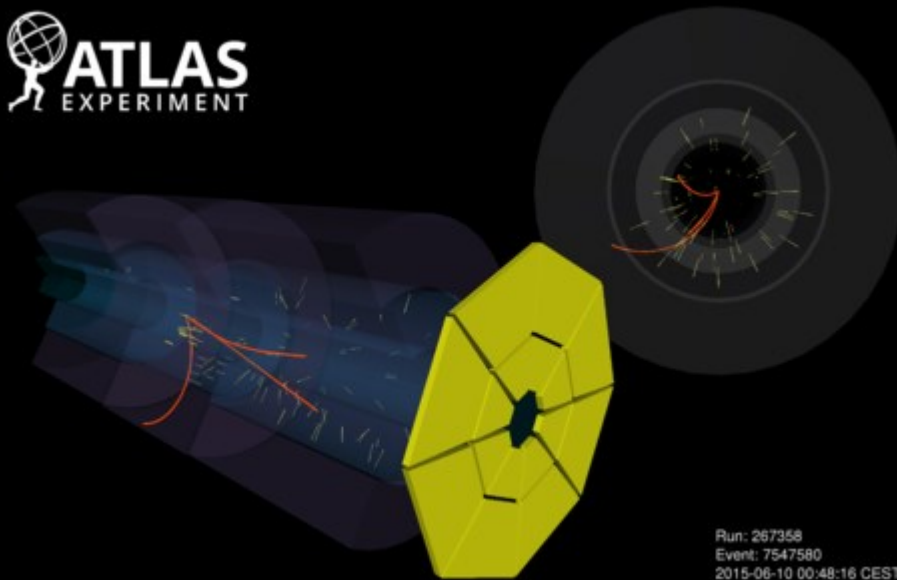
ATLAS
EXPERIMENT



Run: 267358
Event: 7546226
2015-06-10 00:48:16 CEST

Inclusive events

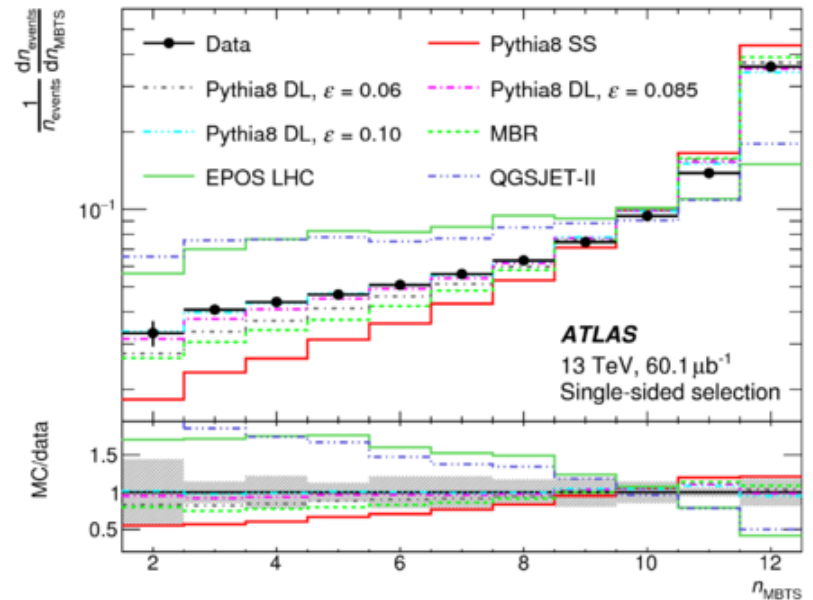
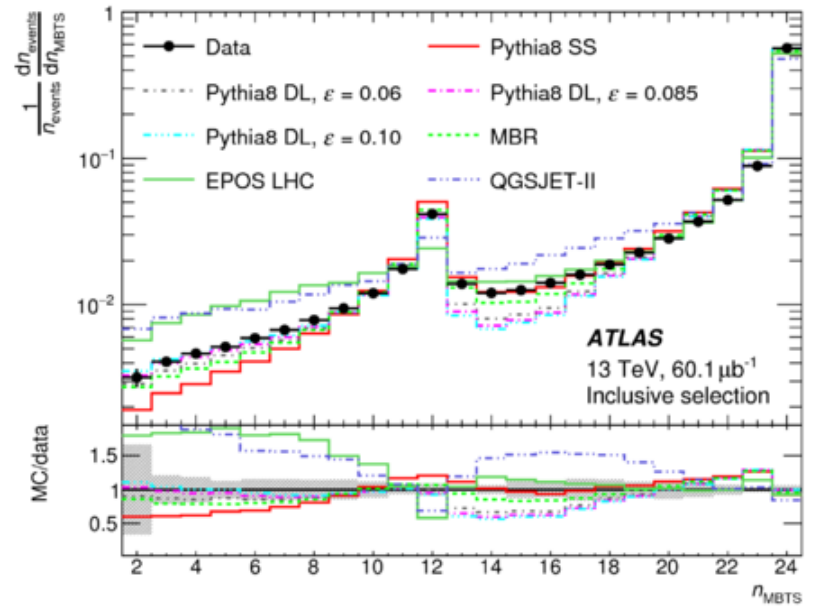
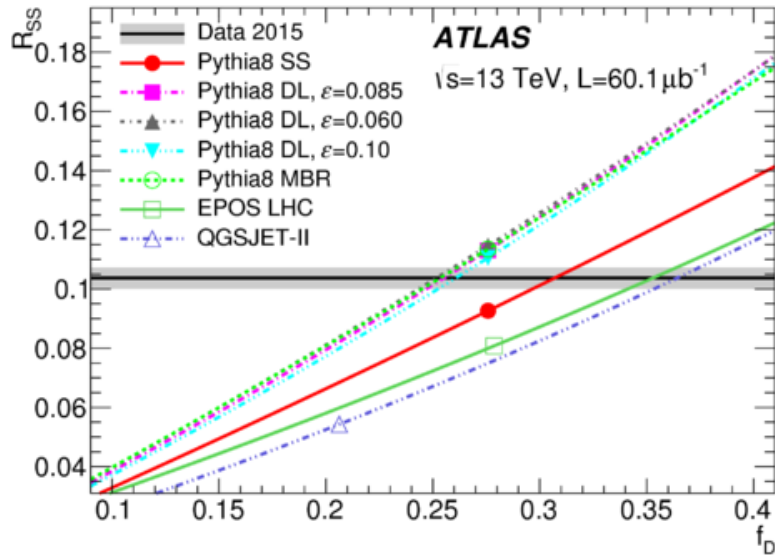
ATLAS
EXPERIMENT



Run: 267358
Event: 7547580
2015-06-10 00:48:16 CEST

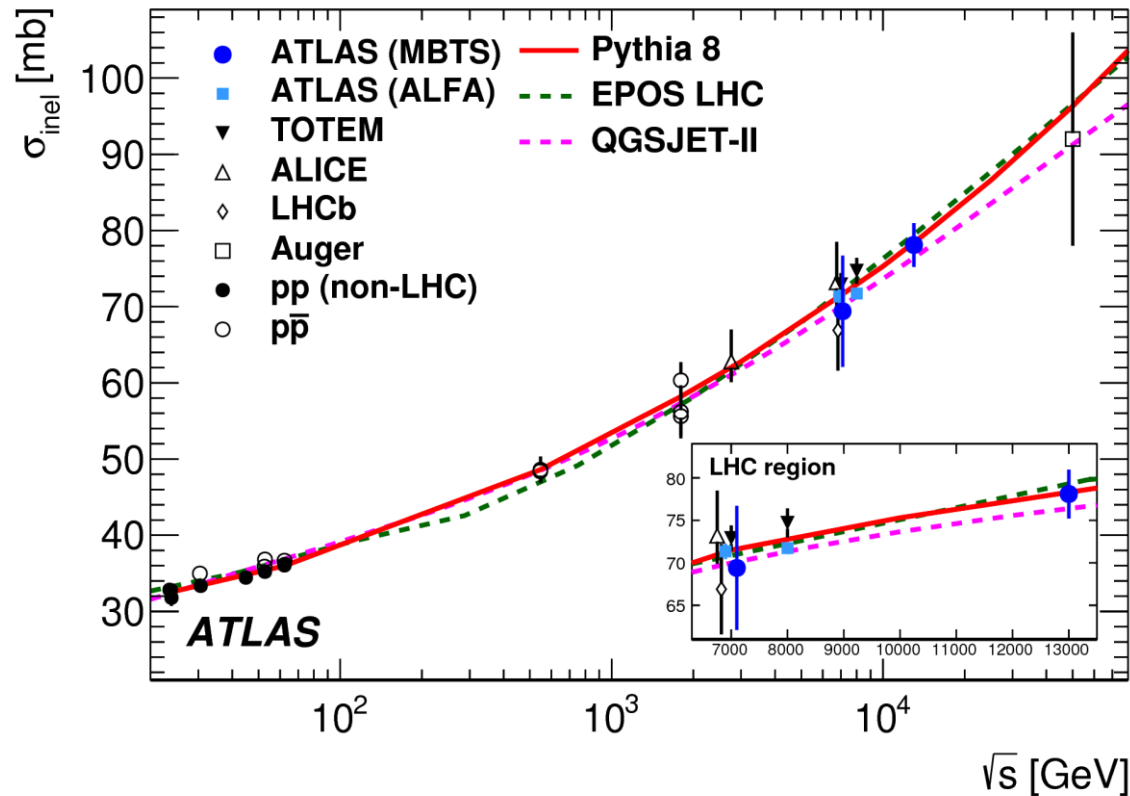
Single-sided events (mostly SD)

Diffraction fraction and MBTS hits



- $R_{SS} = (\text{single-sided})/\text{inclusive}$
 - EPOS/QGSJET は R_{SS} を説明するにはより多い diffraction 必要
 - これらのモデルは2個以上 MBTS にヒットを残す可能性がデータより大きい

13 TeV inelastic cross section σ_{inel}

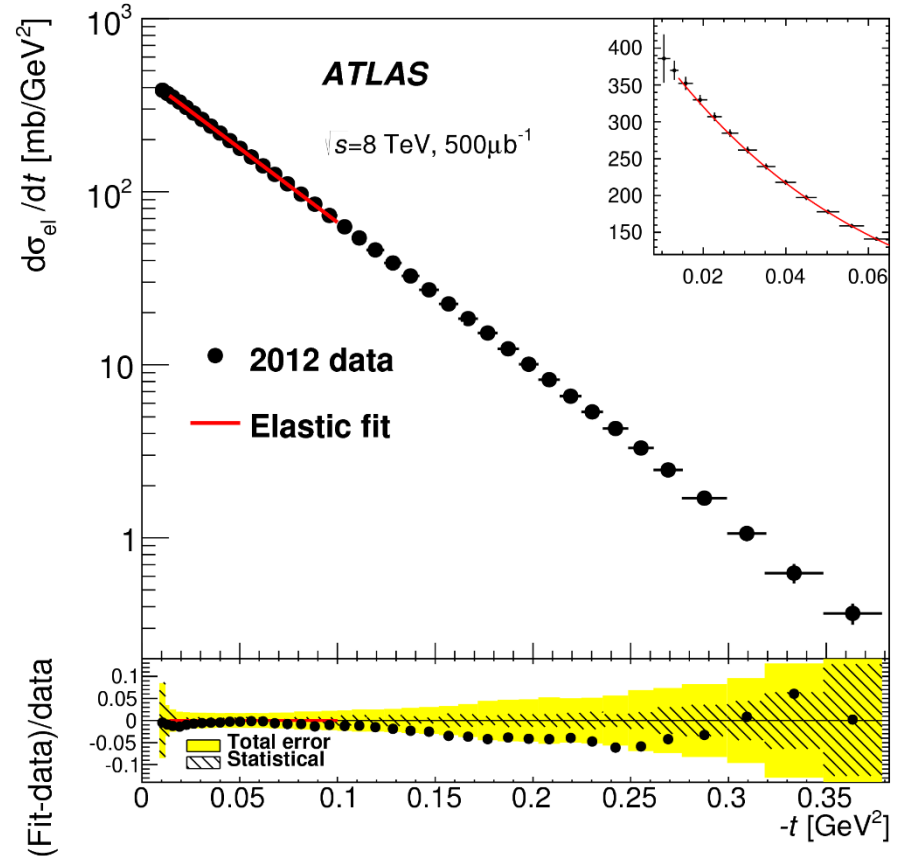


- Uncertainty due to the diffractive fraction f_D is small
- Extrapolation for $\xi < 5 \times 10^{-6}$: 9.9 ± 2.4 mb
 - “total” inelastic: $\sigma_{\text{inel}} = 78.1 \pm 0.6(\text{exp}) \pm 2.4(\text{extrap.})$ mb

Total cross section from optical theorem

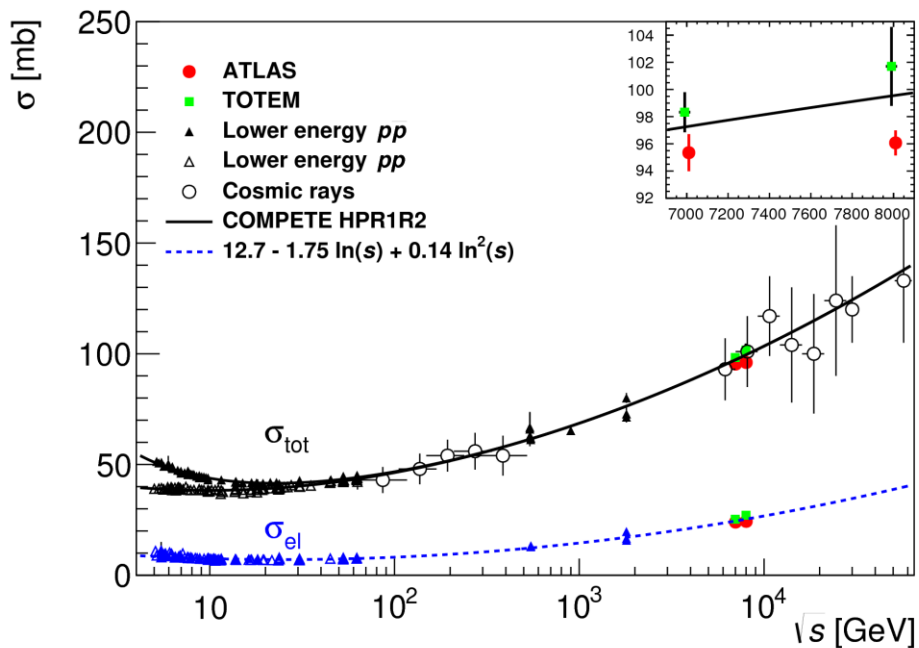
- t –distribution measured by double-arm Roman pots
 - ALFA scintillating fibres by ATLAS
 - TOTEM around the CMS IP
- ALFA uses luminosity for absolute cross section
- TOTEM does not depend on luminosity measurement

$$\sigma_{tot} = \frac{16\pi}{1 + \rho^2} \left(\frac{dN_{el}}{dt} \right) \Big|_{t=0}$$

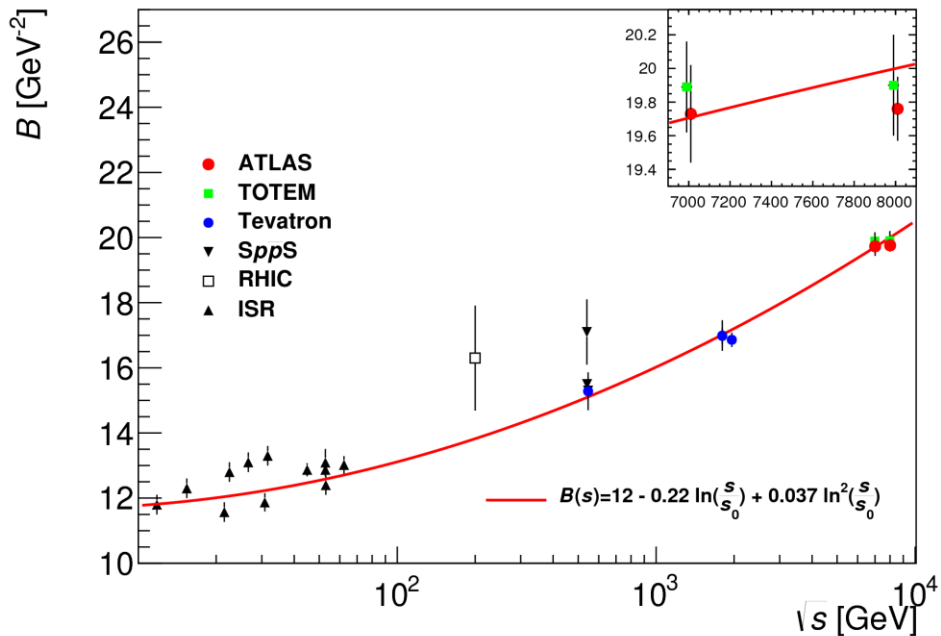


(b)

Results



(a)

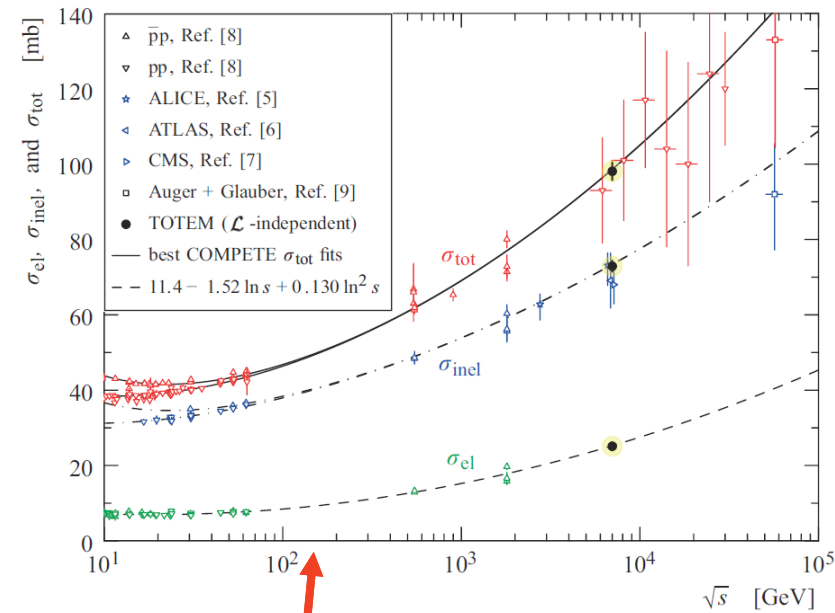


(b)

- Some tension between two results
 - slope results agree, though

Why are we bothered by soft physics?

- Pedagogical arguments:
 - Elastic cross section increases with $s^{2\epsilon}$, while total is s^ϵ : this should break down at some energy
 - Multi-parton phenomena (Eikonalisation) is a key to understand how it continues
 - It is an origin of the (super-)string theory
- Practical arguments:
 - Both elastic and diffractive processes are non-negligible in pp collisions.
 - It is essential to understand them for building a good model in simulating minimum-bias events, which are used for pile-up simulation



Growing faster than σ_{tot} !