DIFFRACTION AT THE LHC

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THE PLAN

- **PART 1:**
  - WHAT DIFFRACTION?
  - SIGNATURES OF DIFFRACTIVE PROCESSES
- **PART 2:**
  - EXPERIMENTS & RESULTS AT THE LHC
  - FUTURE PLANS

WHAT DIFFRACTION?*

DIFFRACTIVE SCATTERING PROBES THE HADRONIC VACUUM

- DIFFRACTIVE SCATTERING IS CHARACTERIZED BY VACUUM FLUCTUATIONS IN THE PERIFERY OF INITIAL STATE HADRONS
- HOW TO QUANTIFY THESE FLUCTUATIONS, THEIR CONTENT AND DYNAMICS?

SOFT DIFFRACTION DEALS WITH QUARK-GLUON STATES CONFINED WITHIN HADRONS

- QCD IS THE THEORY BEHIND – BUT IT IS USEFUL ONLY IN CASE PERTURBATION THEORY CAN BE USED AT SMALL DISTANCES - HAVING A HARD SCALE IN p_T^2, Q^2!

$\Rightarrow$ SOFT – LONG DISTANCE – PROCESSES CANNOT BE CALCULATED – NEED PHENOMENOLOGICAL MODELS FOR:

σ_{tot} $\sigma_{elastic}$ σ_{diff} $(= \sigma_{SD}+\sigma_{DD}+\sigma_{CD})$

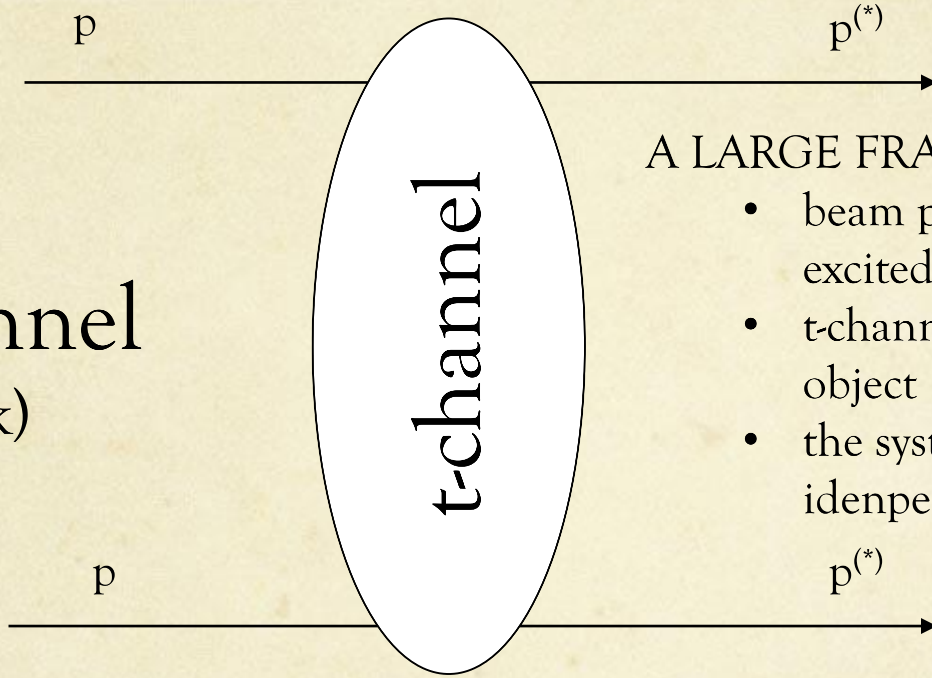
- AT LARGE DISTANCES CONFINEMENT FORCES TAKE OVER – BINDING FORCES BETWEEN QUARKS RESPONSIBLE FOR STATIC PROPERTIES OF HADRONS – DIFFRACTIVE SCATTERING TO PROBE THESE.

DIFFRACTIVE SCATTERING MAPS OUT CONFIGURATIONS OF PARTONS (QUARKS AND GLUONS) CONFINED WITHIN HADRONS

- SPACE-TIME EVOLUTION OF HADRON-HADRON SCATTERING

- QCD ASYMPTOPIA - QUARK-GLUON CONFINEMENT

DIFFRACTION IS DESCRIBED AS A PRODUCTION (s-channel) OR AS AN EXCHANGE (t-channel) PROCESS



s-channel

(this talk)

A LARGE FRACTION OF EVENTS WITH:

- beam particles intact (elastic) or excited into a diffractive state *
- t-channel exchange of a colourless object
- the systems created hadronize idenpendently, produce rap gaps

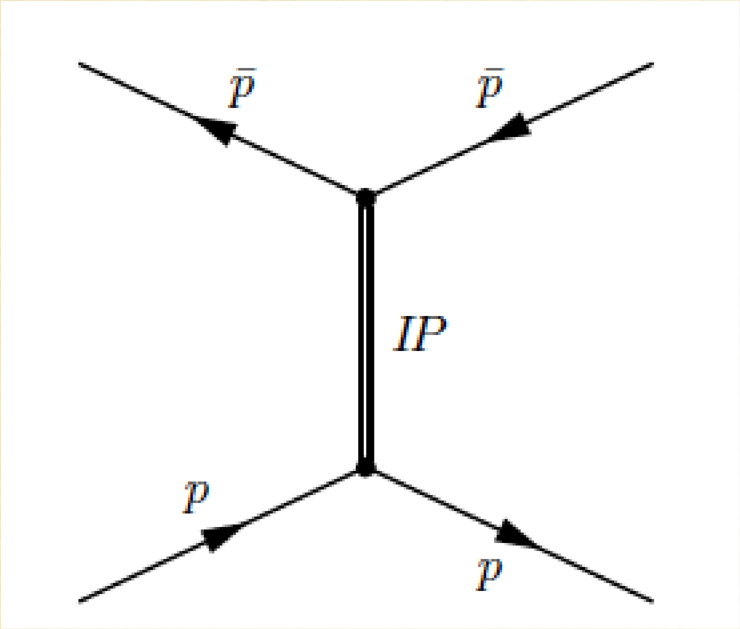
Bjorken's definition (out of frustration?):
"A process which causes rapidity gaps that are not exponentially suppressed."

⇒ Optical analogy: Fraunhofer scattering.

DIFFRACTION HAS AN OPTICAL ANALOGY

- THE TWO APPROACHES BOTH USE AN ANALOGY TO (FRAUNHOFER) DIFFRACTION IN OPTICS:
  - MUELLER – REGGE MODEL
  - GOOD – WALKER FORMALISM
- THESE MODEL APPROACHES ARE SUPPLEMENTED BY:
  - saturation models, semiclassical approaches, dipole models, colour (re-)connection. and perturbative QCD – BFKL a 'microscopic' description of diffraction...

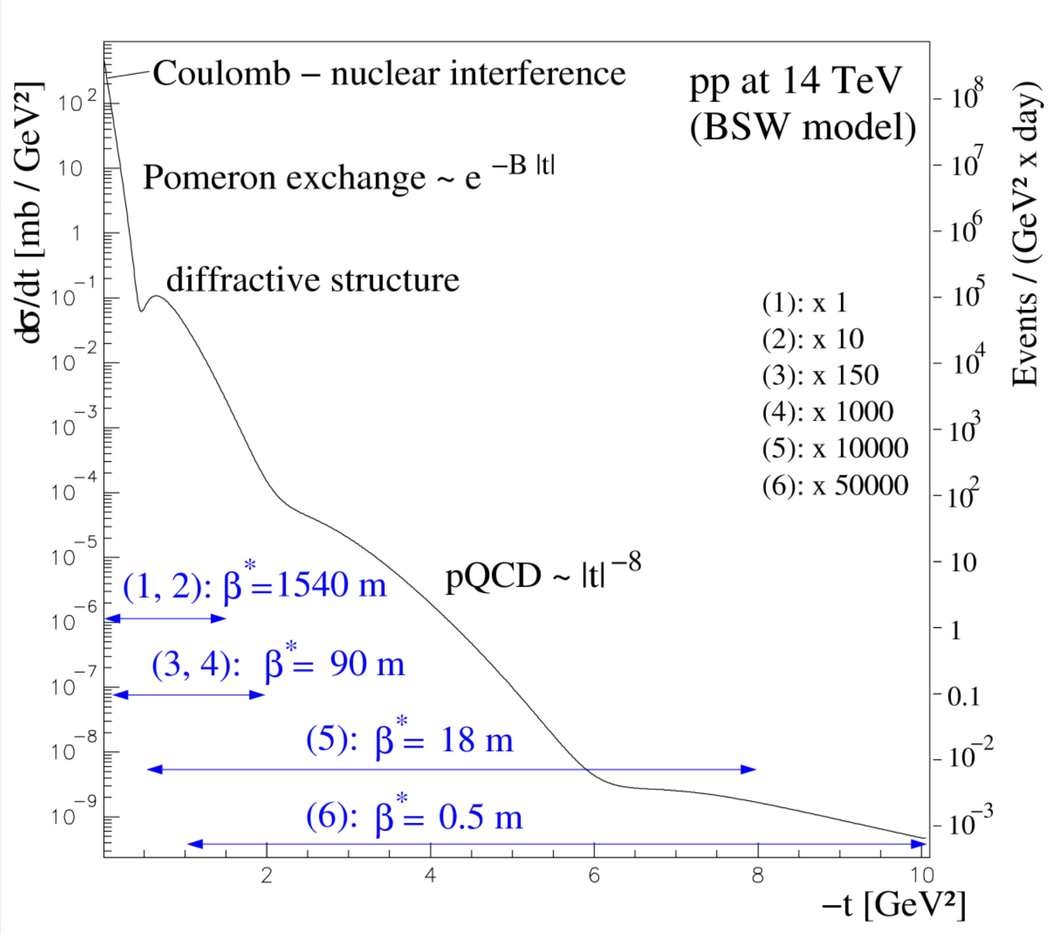
ELASTIC SCATTERING IS DIFFRACTIVE



$$\bar{p}p \rightarrow \bar{p}p$$

ELASTIC CROSS SECTION PROJECTS THE SHADOW OF A COMPLEX PROTON

12 orders of magnitude



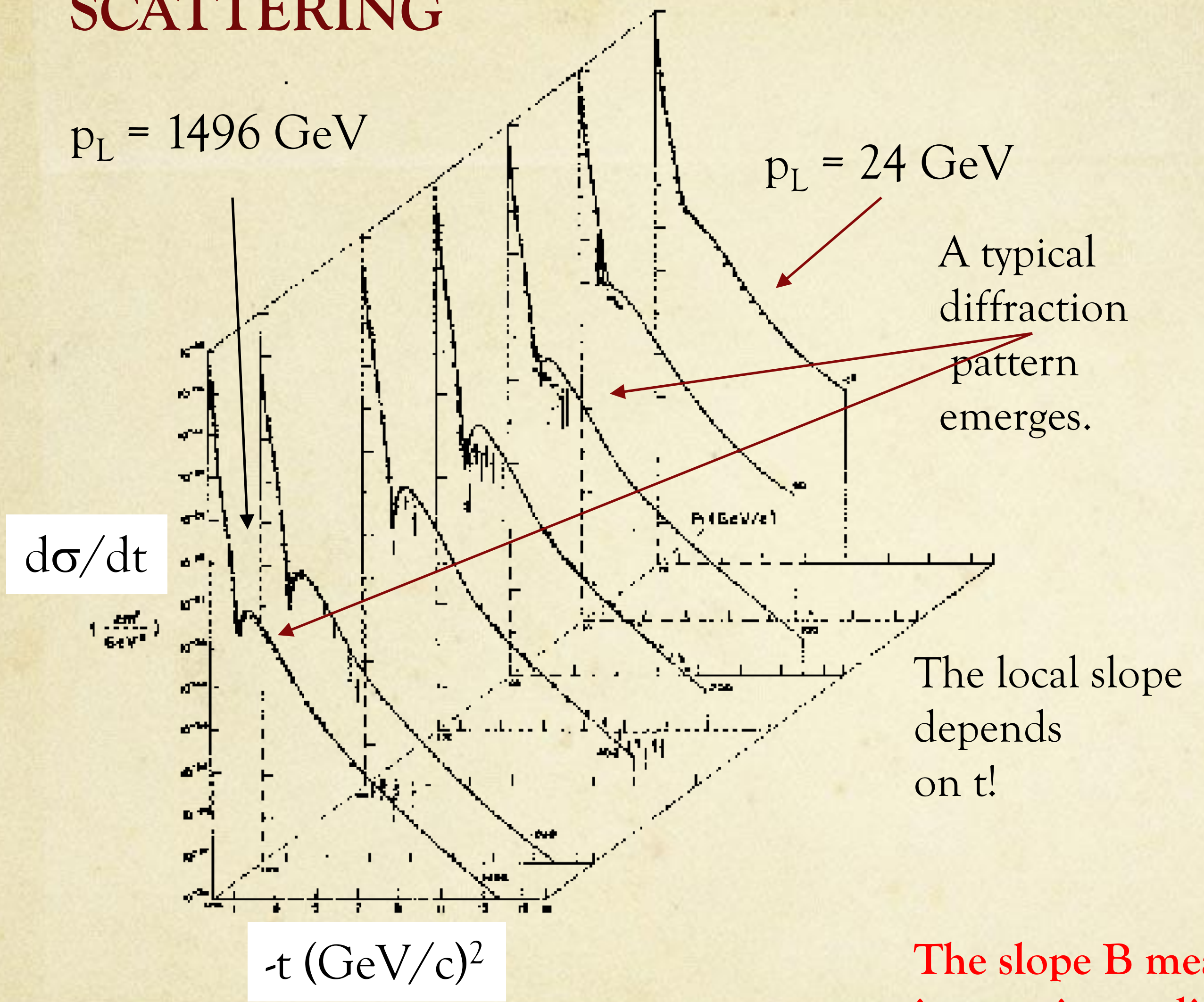
$d\sigma_{el}/dt$ yields:

- pp *interaction radius* (slope of the $d\sigma_{el}/dt$ distribution)
- with the measurement of the total inelastic rate - the *total pp cross section*,
- a test of the *Coulomb-nuclear Interference* (expected to have an effect over *large* interval in −t).
- a measurement of the *ratio of the real and imaginary parts* of the forward pp scattering amplitude, ρ = ReA(s,t)/ImA(s,t)

⇒ through dispersion relations, a precise measurement of ρ will constrain σ_{tot} at substantially higher energies

⇒ "SHADOW SCATTERING"

ISR RESULTS – CHARACTERISTICS OF ELASTIC SCATTERING



- diffractive peak *shrinks* – interference *dip* moves to smaller t
- at $-t \geq 1$ GeV^2 little $\sqrt{s}$ dependence, $d\sigma/dt \propto 1/t^8$ a la Donnachie&Landshoff
- exponential fall-off up to $-t \approx 10$ GeV^2 ?
- size of the interaction region $\propto B(s)$

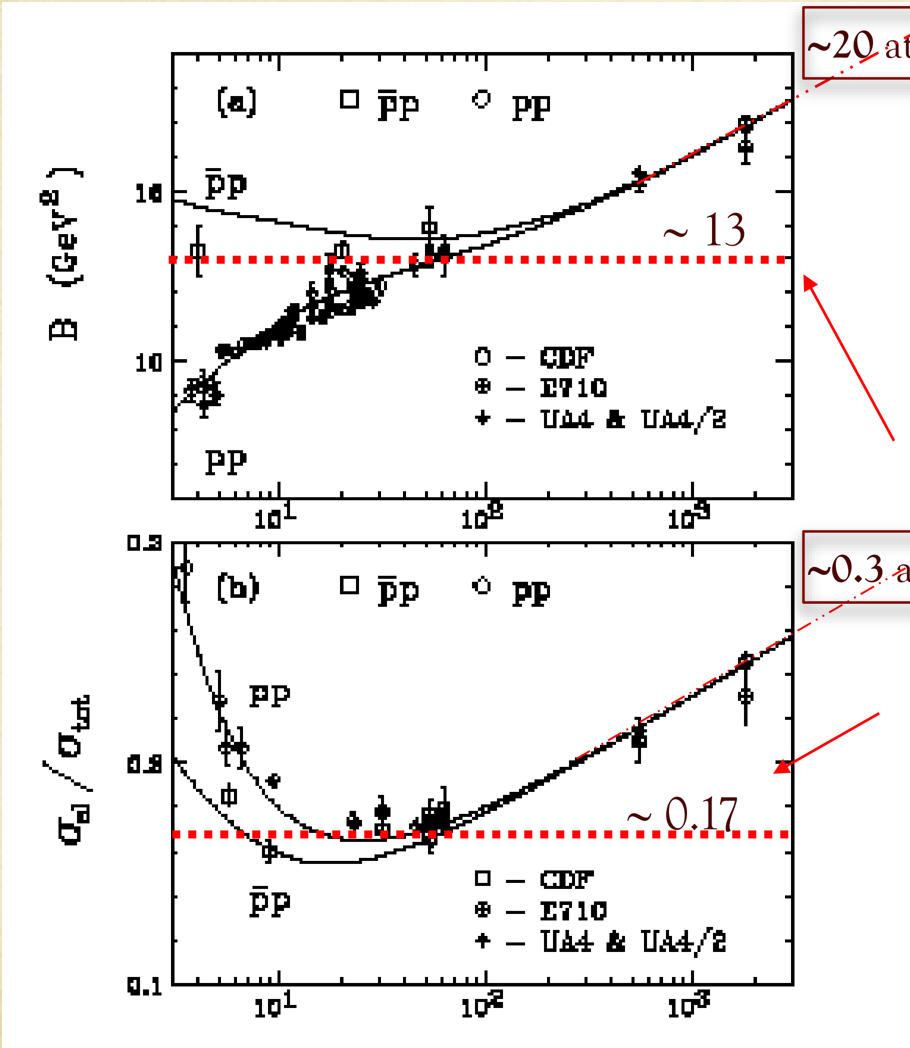
The slope B measures the pp interaction radius

WHERE IS THE BLACK DISC LIMIT?

$\sigma_{el}/\sigma_{tot} = ½$

B~32 at the black disc limit?

The black disc limit reached at 10^8 GeV?



~20 at the LHC, <b²> ≈ 1.6fm²

Forward elastic slope shrinks
⇒ effective interaction radius of proton grows (∝ lns)

The values of the slopes agree with the optical picture, i.e. with a fully absorbing disc of radius R for which $B = R^2/4$.

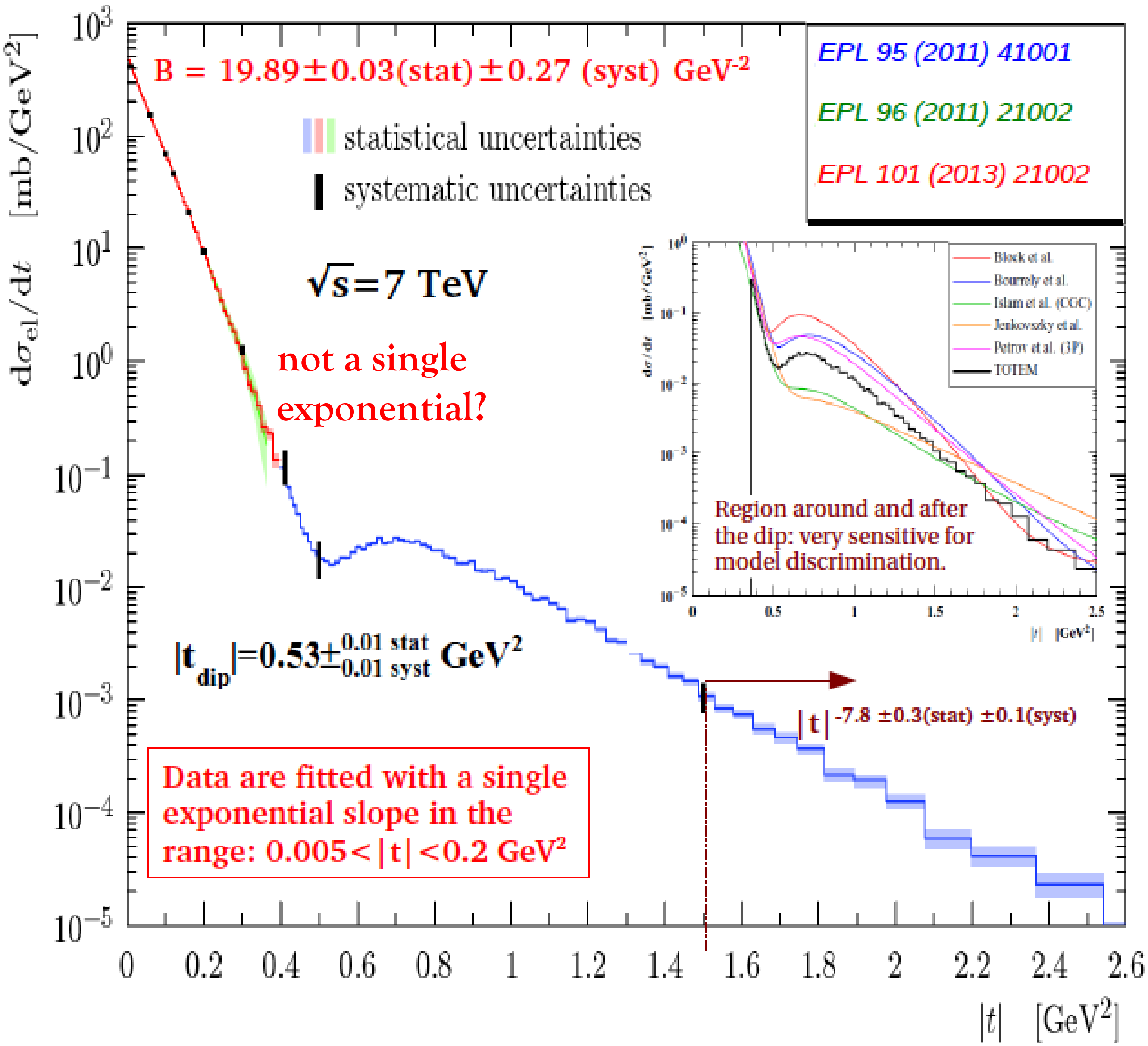
For a proton with $R \approx 1/m_\pi$ (m_π = π meson mass):
$B \approx 13$ GeV^{-2}

~0.3 at the LHC

However: Scattering on a black disc: $\sigma_{el}/\sigma_{tot} = ½$, while the data (at $\sqrt{s}$ corresponding to $B \sim 13$ GeV^{-2}) gives $\sigma_{el}/\sigma_{tot} = 0.17$…
⇒ **the proton is semi-transparent**
⇒ QCD colour transparency!

Mixture of scattering states with different absorption probabilities is required for diffractive scattering to take place.

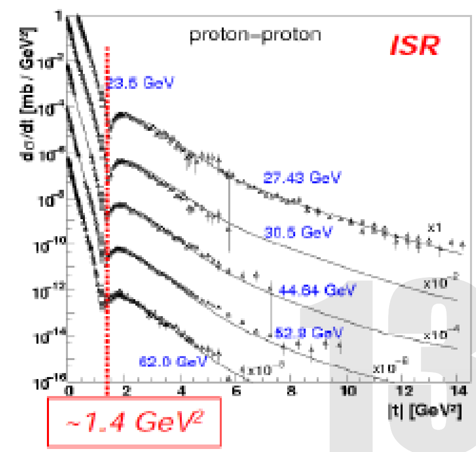
Elastic scattering results: $5 \cdot 10^{-3} < |t| < 2.5$ GeV^2 @ 7 TeV



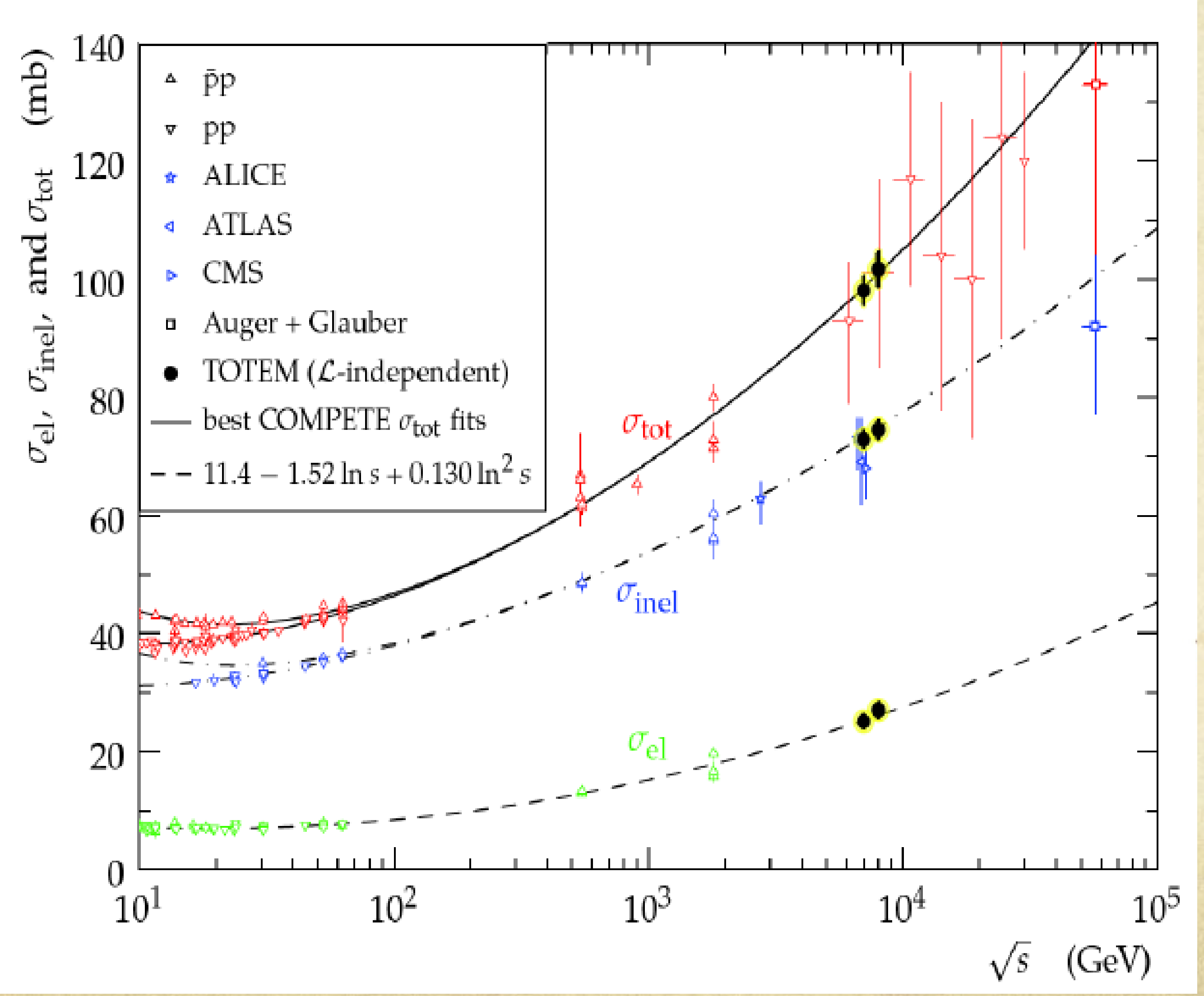
EPL 95 (2011) 41001	**0.36 <|t|< 2.5 GeV²**
EPL 96 (2011) 21002	**0.02 <|t|< 0.33 GeV²**
EPL 101 (2013) 21002	**$5 \cdot 10^{-3}$ <|t|< 0.4 GeV²**

Shrinkage of the forward peak:

- minimum moves to lower |t| with increasing CM energy
- exponential slope grows with the CM energy



SUMMARY OF CROSS SECTION MEASUREMENTS AT THE LHC

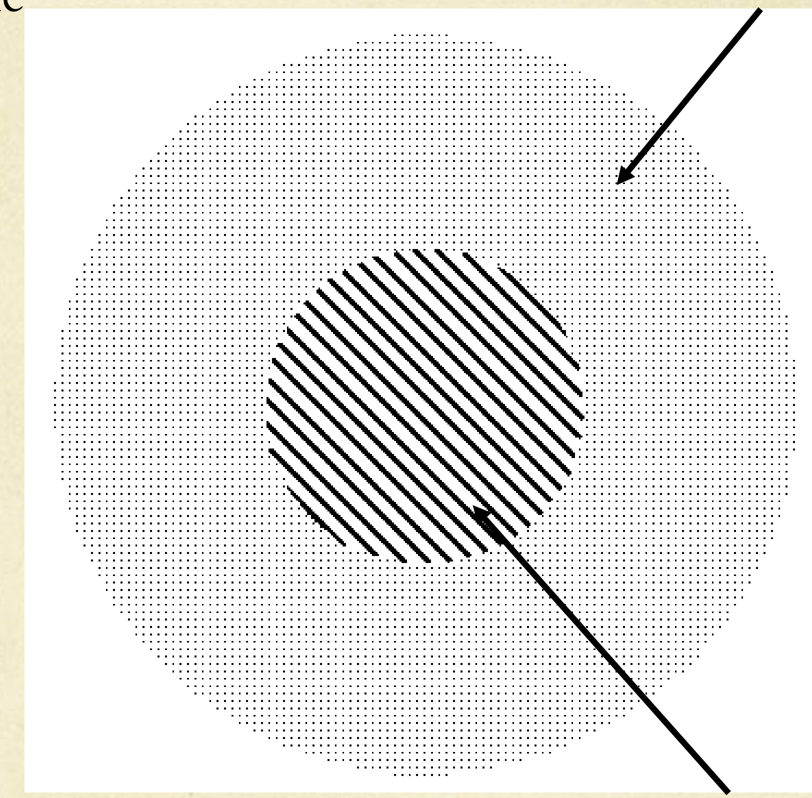


MUELLER-REGGE AND GOOD-WALKER APPROACH BOTH HAVE AN OPTICAL ANALOGY – FRAUNHOFER SCATTERING*

- **A coherent phenomenon** that occurs when a beam of light meets an obstacle with dimensions comparable to the wavelength of incoming light.
- As long as the *wavelength is much smaller than the dimension of an obstacle*, there is a geometrical **shadow**.

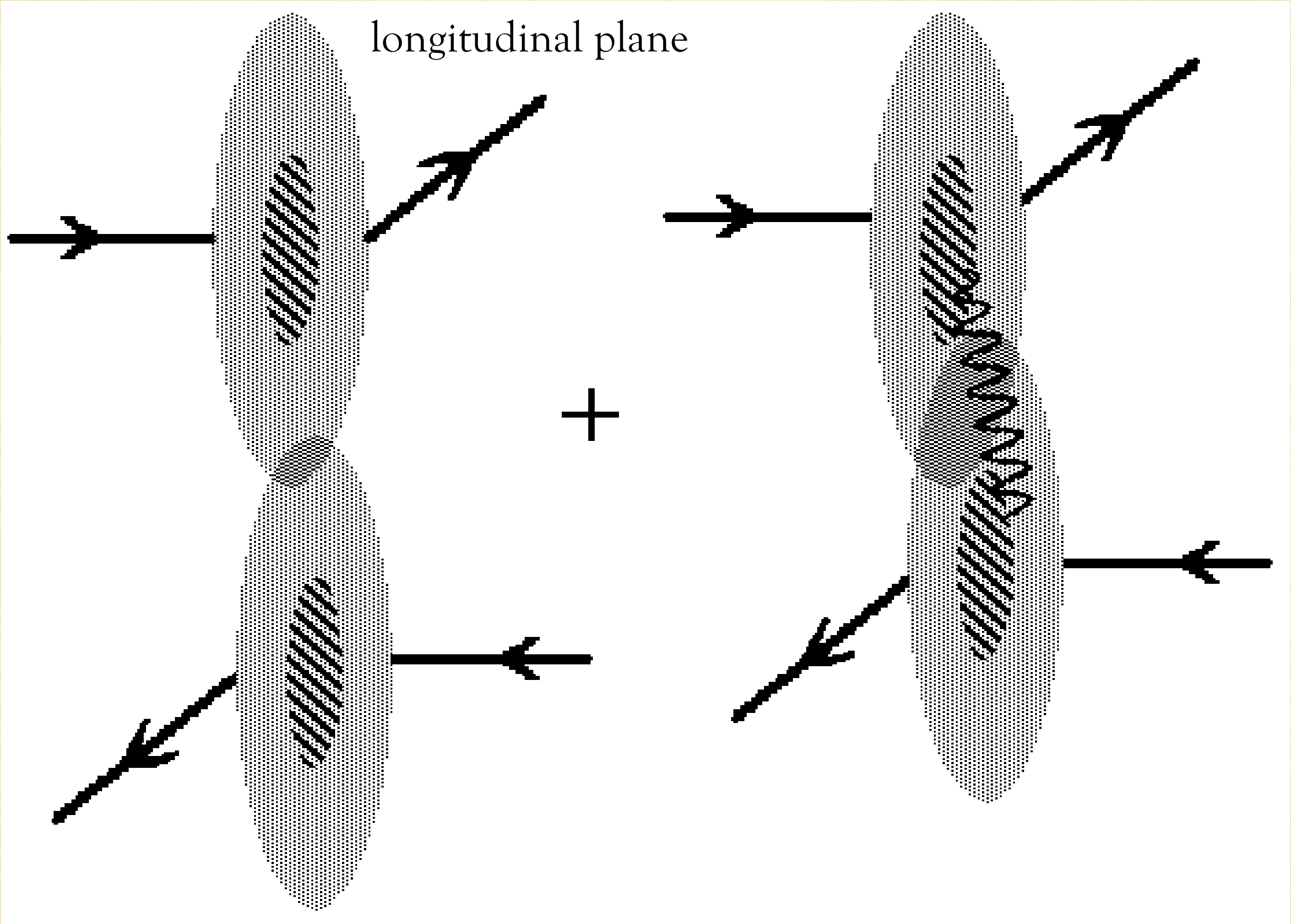
Optical analogy by the Landau school: (L.D. Landau and I.Y. Pomeranchuk, Zu.Eksper.Teor.Fiz.24(1953)505, E.Feinberg, NC suppl.3(1956)652, A.I. Akhiezer and Y.I. Pomeranchuk, Uspekhi, Fiz.Nauk.65(1958)593, A. Sitenko, Uspekhi, Fiz.Nauk.67(1959)377, V.N. Gribov, Soviet Jetp 29(1969)377.)

GEOMETRICAL PICTURE OF PROTON…



proton at rest – what happens in a high energy collision?

LORENTZ CONTRACTED PROTONS INTERACT

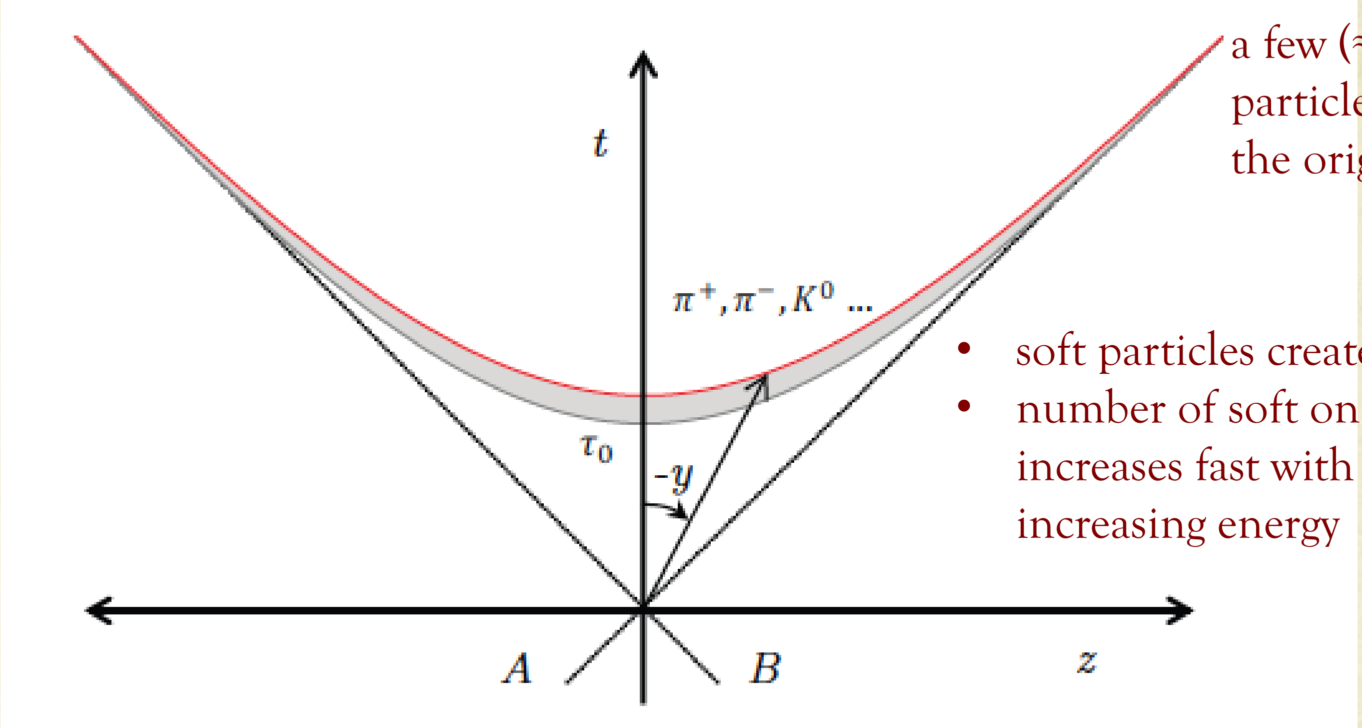


SOFT DIFFRACTION

HARD DIFFRACTION

SIGNATURES OF DIFFRACTIVE SCATTERING

SPACE-TIME EVOLUTION

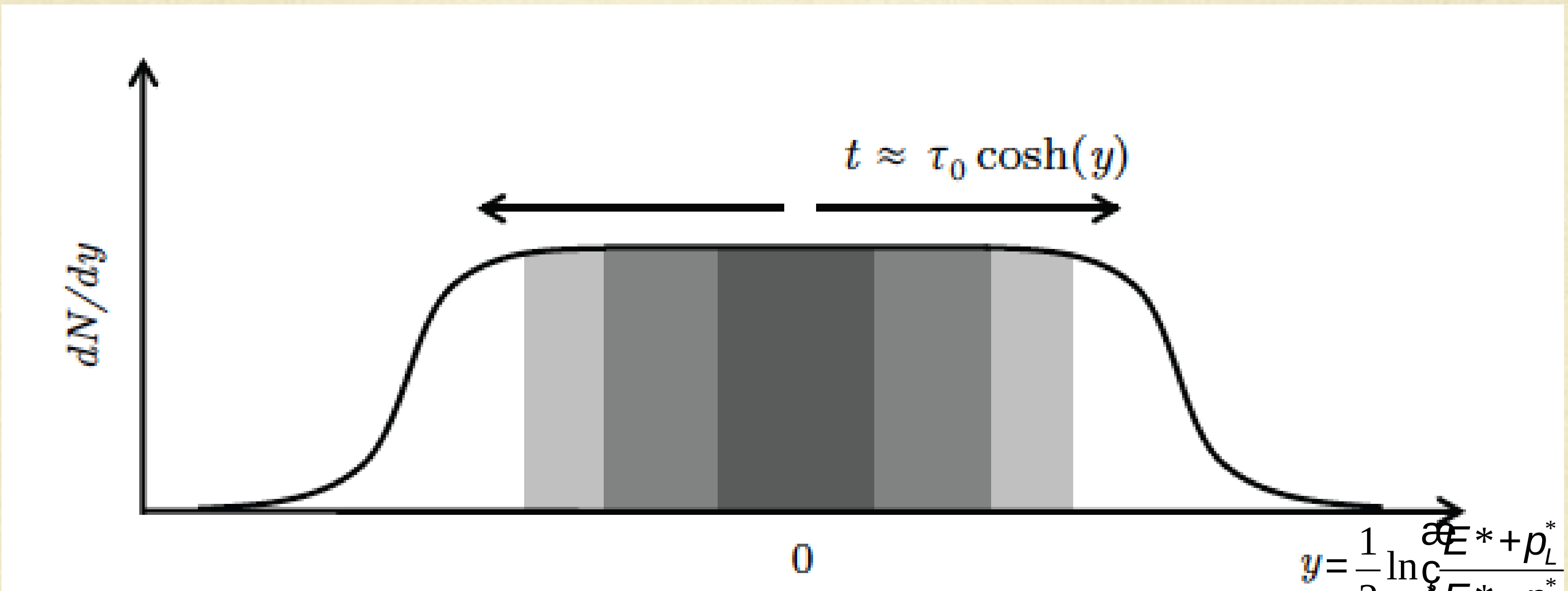


a few (≈ 3) fast particles remember the original parton

- soft particles created first!
- number of soft ones increases fast with increasing energy

Hadron collision as a chain reaction initiated by wee partons: At first, only a small c.m.s. domain of partons within $|\Delta y| \approx 1$ around y=0 is excited. Subsequent to this initial excitation, de-excitation "cooling" takes place by $\tau_0 \approx$ 1fm/c through hadron emission that, in turn, excites neighbouring domains with a characteristic time of $t \approx \tau_0 \cosh(y)$.

RAPIDITY SPACE – TIME WINDOW TO HADRON-HADRON SCATTERING



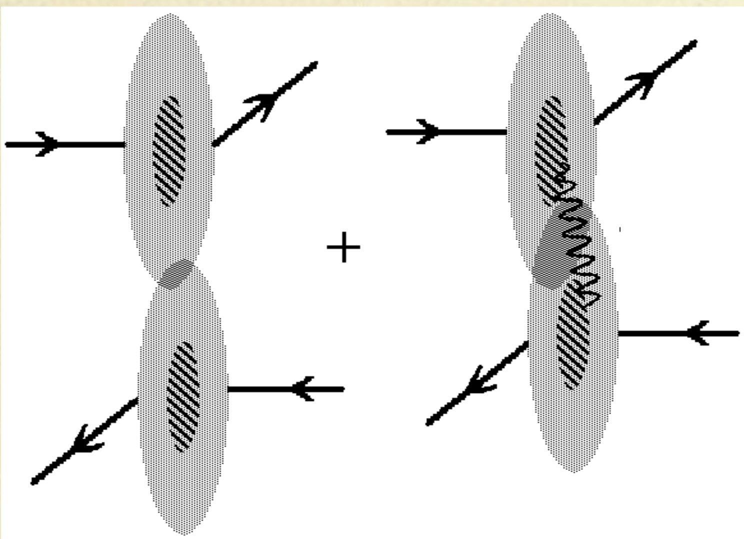
$$y = \frac{1}{2} \ln \left(\frac{E^* + p_L^*}{E^* - p_L^*} \right)$$

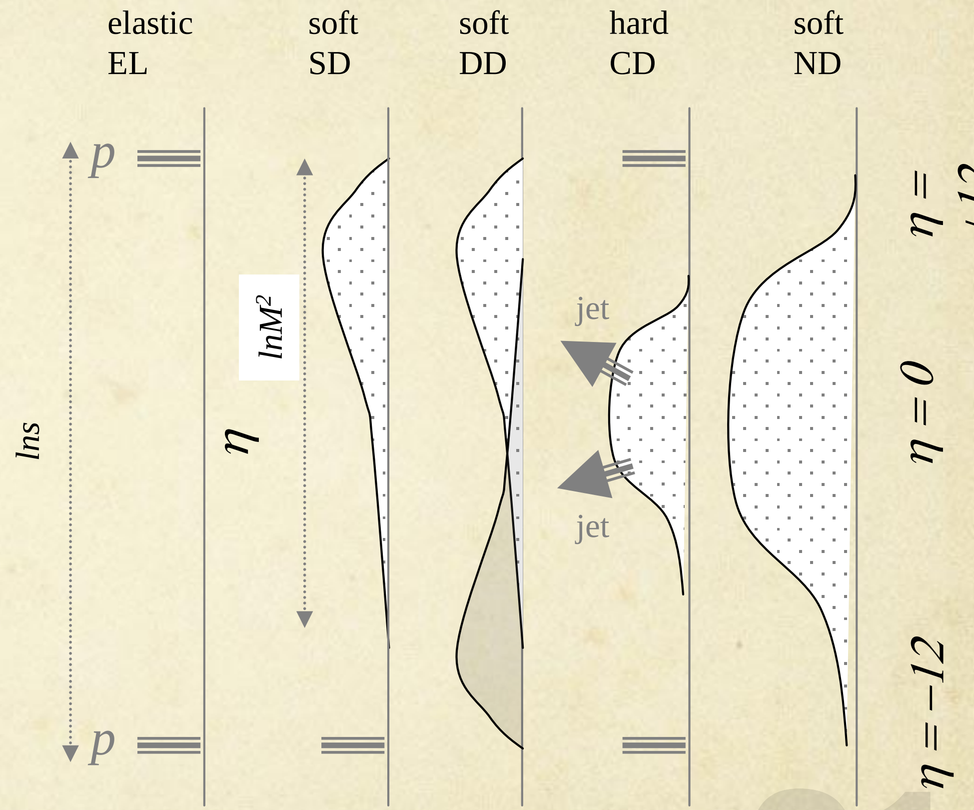
Assume that the colliding hadrons are Lorentz contracted into narrow discs. In collision, hadrons are formed and fill up the kinematically allowed longitudinal momentum space. A uniform rapidity distribution of final state particles results.

PROFILES OF DIFFRACTIVE SCATTERING AS SEEN IN THE RAPIDITY SCREEN

soft diffractive scattering

hard diffractive scattering

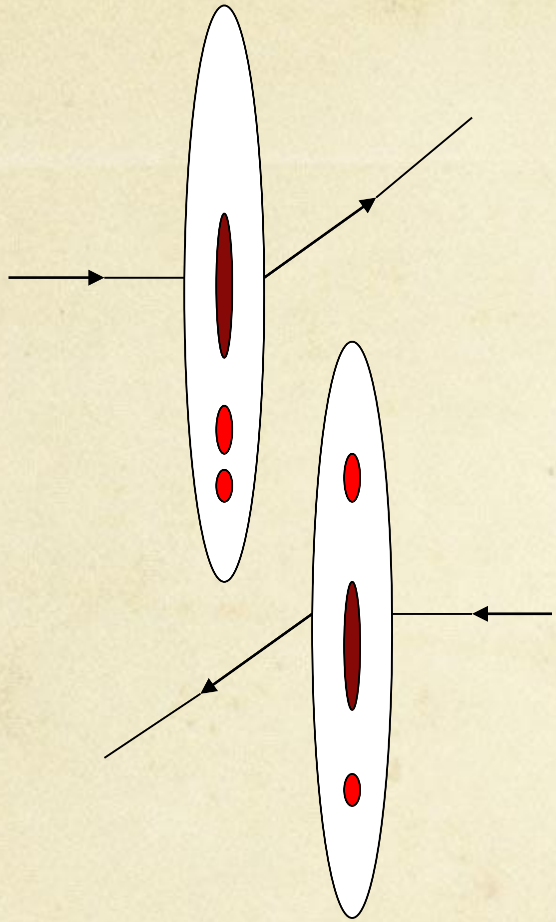


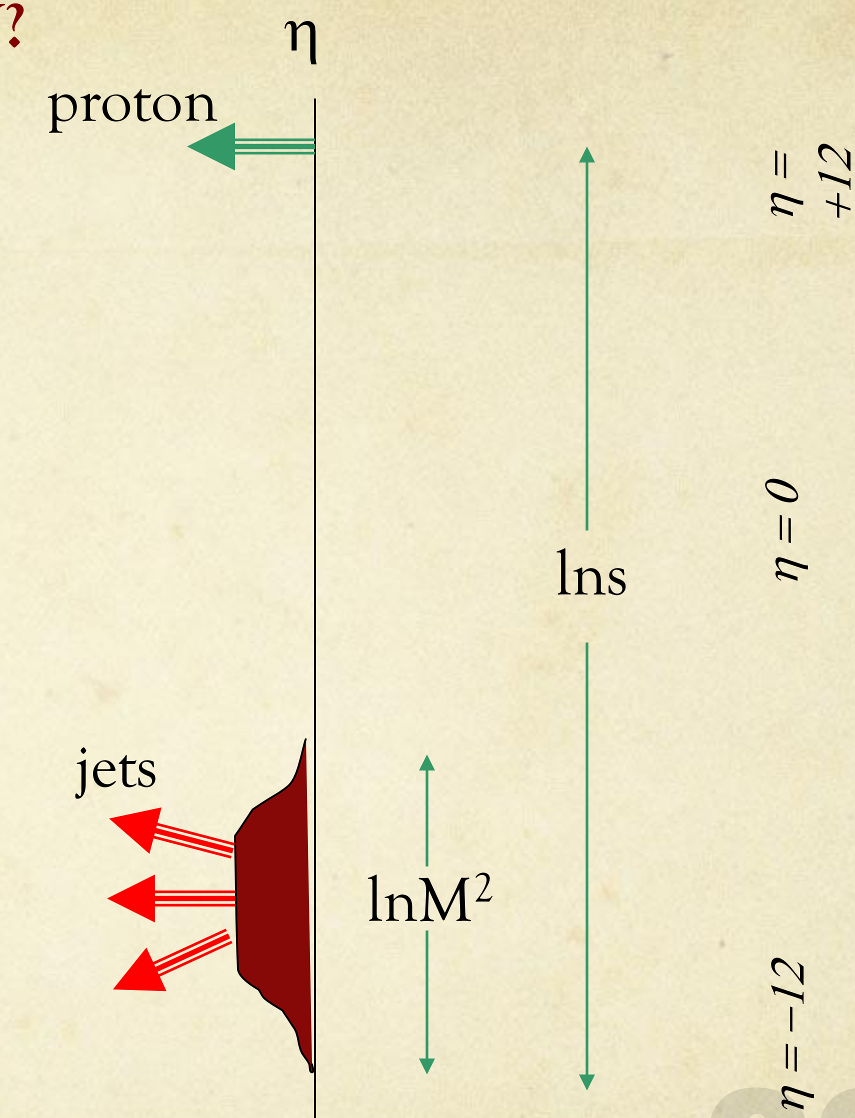


-low & high masses pose a challenge!

pseudorapidity axis $h = -\ln(\tan(q/2))$

MULTIPLE GAPS IN RAPIDITY?





’hot spots’ – vacuum fluctuations
of the ’wee’ partons in the gluon cloud
of protons?

SIGNATURES

- TRADITIONALLY, LOOK FOR LARGE RAPIDITY GAPS (LRGs) OF $\Delta\eta \geq 3$ UNITS
- CORRESPONDS TO $\xi = 1\text{-}p_z^f/p_z^i = M_X^2/s \leq 0.05$
- REQUIRE NO TRACKS OR ENERGY DEPOSITS WITHIN THE LRG
- HARD DIFFRACTION: Jets, heavy quarks, W's,..

RAP GAPS AS OBSERVABLES

- PARTON RE-SCATTERINGS
- CALORIMETER NOISE, LACKING TRACK E_T/p_T ACCEPTANCE...
- FLUCTUATIONS IN THE QCD CASCADES PRODUCED IN NON-DIFFRACTIVE EVENTS
- KINEMATICAL OVERLAPS IN RAPIDITY (DUE TO LIMITED PHASE SPACE)
- LACKING ANGULAR COVERAGE

FOR SEEING THE RAP GAPS, NEED GOOD COVERAGE in p_T: min(p_T) ≲ 100 MeV

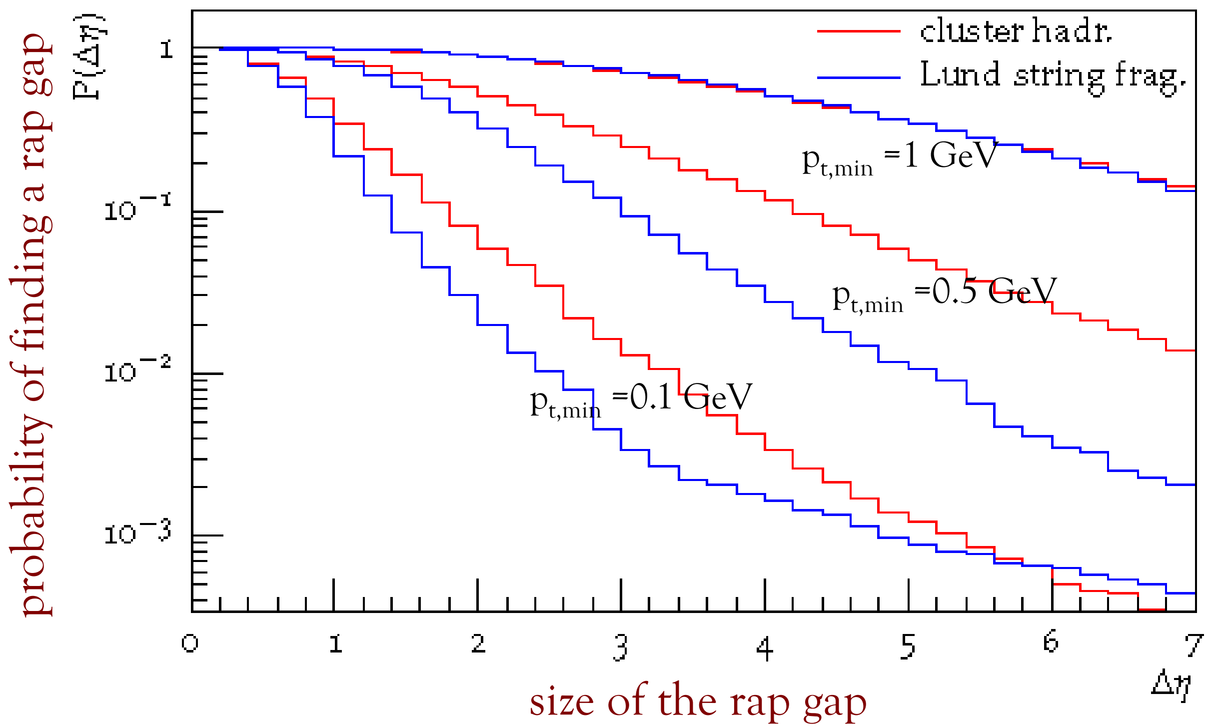


Fig. 4. Probability for finding a rapidity gap (definition 'all') larger than $\Delta\eta$ in an inclusive QCD event for different threshold $p_\perp$. From top to bottom the thresholds are $p_{\perp,\rm cut} = 1.0$, 0.5, 0.1 GeV. Note that the lines for cluster and string hadronisation lie on top of each other for $p_{\perp,\rm cut} = 1.0$ GeV. No trigger condition was required, $\sqrt{s} = 7$ TeV.

SURVIVAL OF RAPIDITY GAPS

How do the rapidity gaps - created by colourless pomeron exchange - survive (1) inelastic interactions of the spectator partons, (2) soft ”parasite” gluon emissions?

In impact parameter, b_t, space: The amplitude of the diffractive process under study is $M(s,b_t)$. The probability that there is *no extra inelastic interaction* is:

$$S^2 = \int \left|M(s,b_t)\right|^2 \exp\left[-\Omega(b_t)\right] d^2 b_t \,/\, \int \left|M(s,b_t)\right|^2 N d^2 b_t$$

where $\Omega(b_t)$ is the opacity (optical density) of the interaction and $N=\exp(-\Omega^o)$ the normalizing factor where Ω^o denotes the relevant opacity evaluated at $\Omega = 0$.

The survival probability, S^2, depends strongly on the spatial distribution of the constitutents of the relevant subprocess.

THE PLAN

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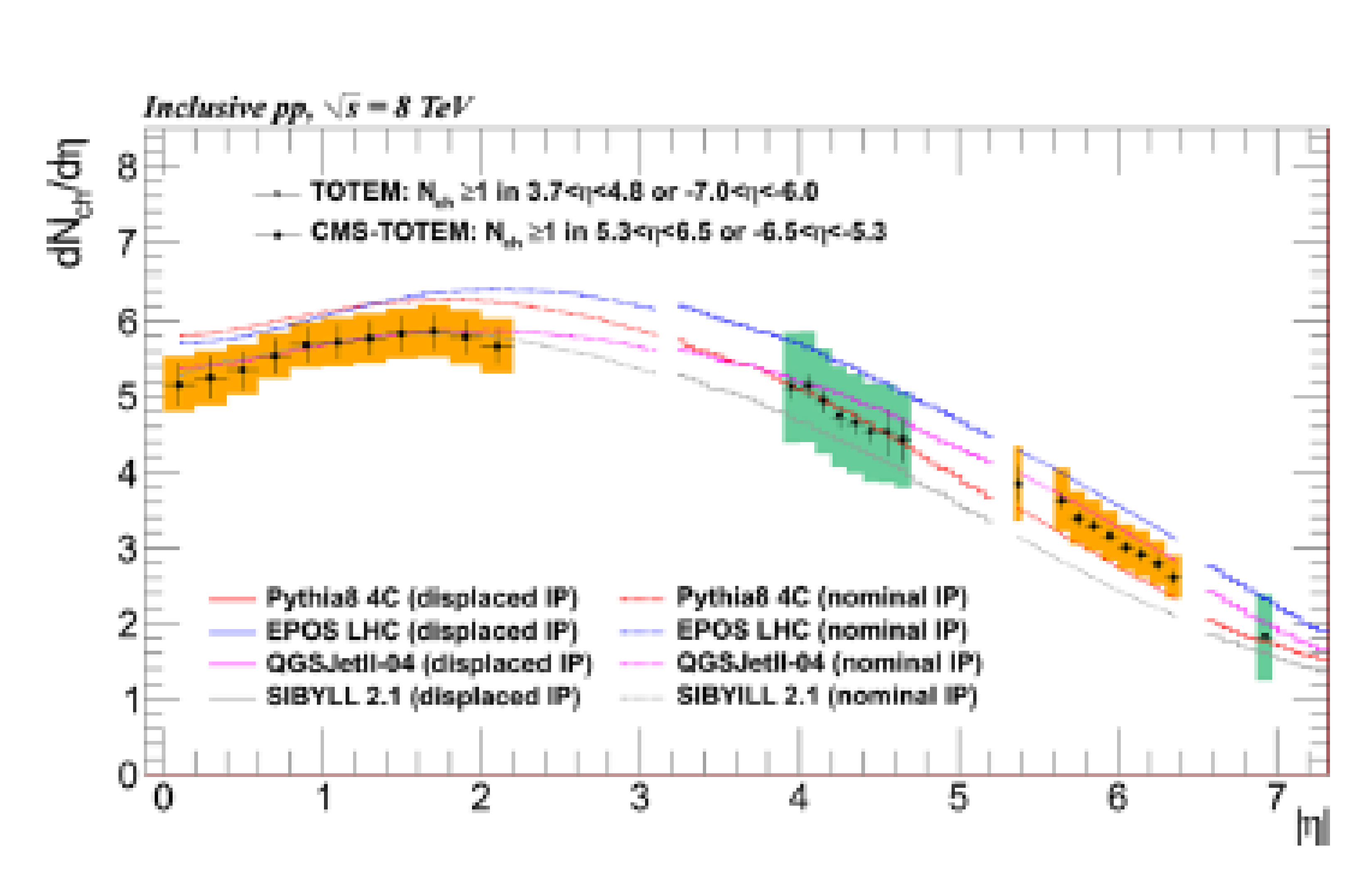
MULTIPLICITIES

FORWARD MULTIPLICITIES

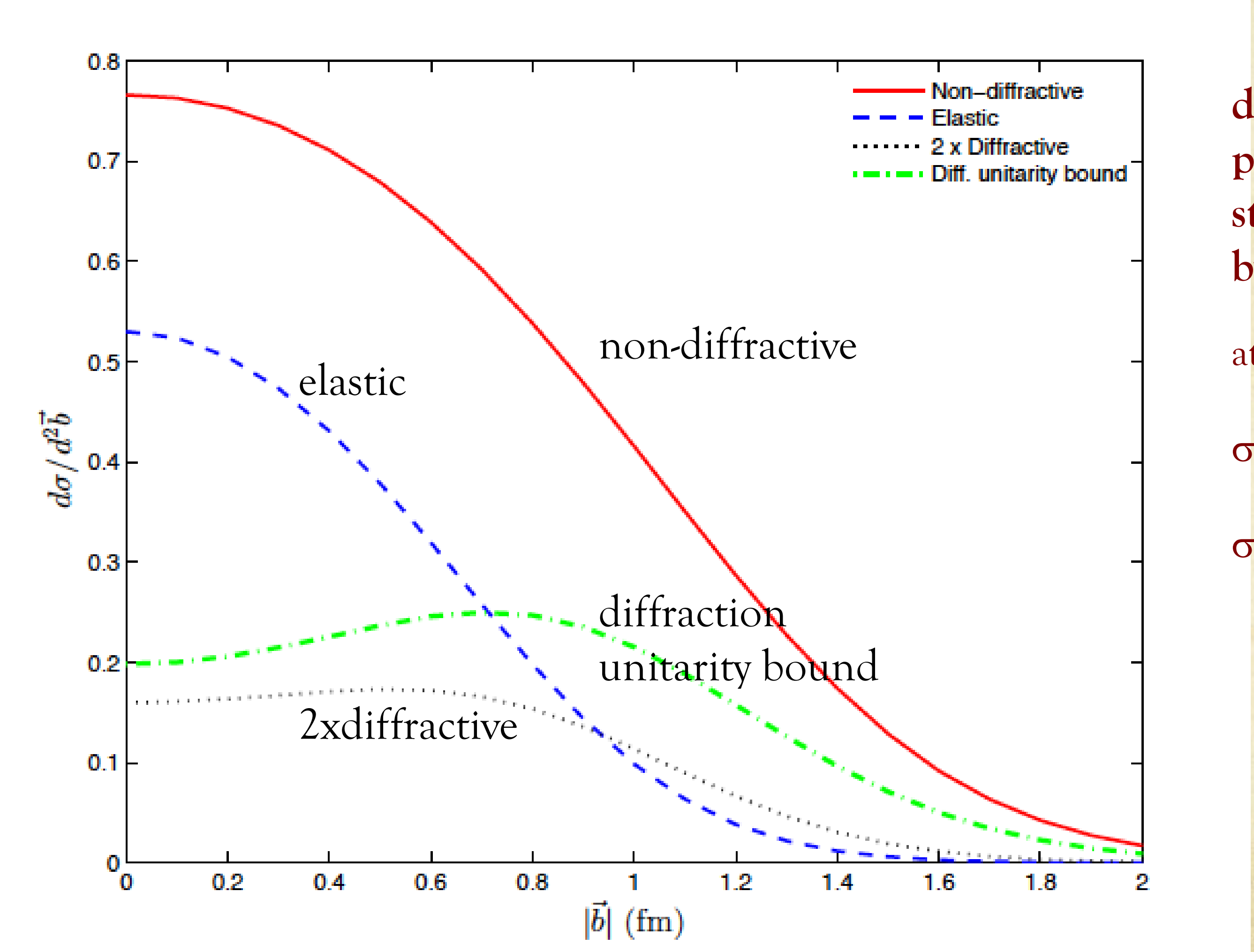


VACUUM FLUCTUATIONS IN PROTONS

GOOD-WALKER APPROACH TO DIFFRACTIVE HADRON SCATTERING

- HADRONS ARE CONSIDERED AS QUANTUM MECHANICAL SUPERPOSITIONS OF QUARK-GLUON STATES
- HADRON-HADRON INTERACTIONS OCCUR BETWEEN THE QUARK-GLUON STATES EXTENDED IN SPACE AND TIME
- A HADRON-HADRON INTERACTION IS CALLED DIFFRACTIVE, IN CASE THE SCATTERING PROCESS CAN BE DESCRIBED AS AN ABSORPTION OF THE HADRON WAVE FUNCTION BY THE NUMBER OF AVAILABLE INELASTICS SCATTERING MODES – DIFFRACTION IS "SHADOW" SCATTERING"

PROTON-PROTON SCATTERING IN THE IMPACT PARAMETER SPACE



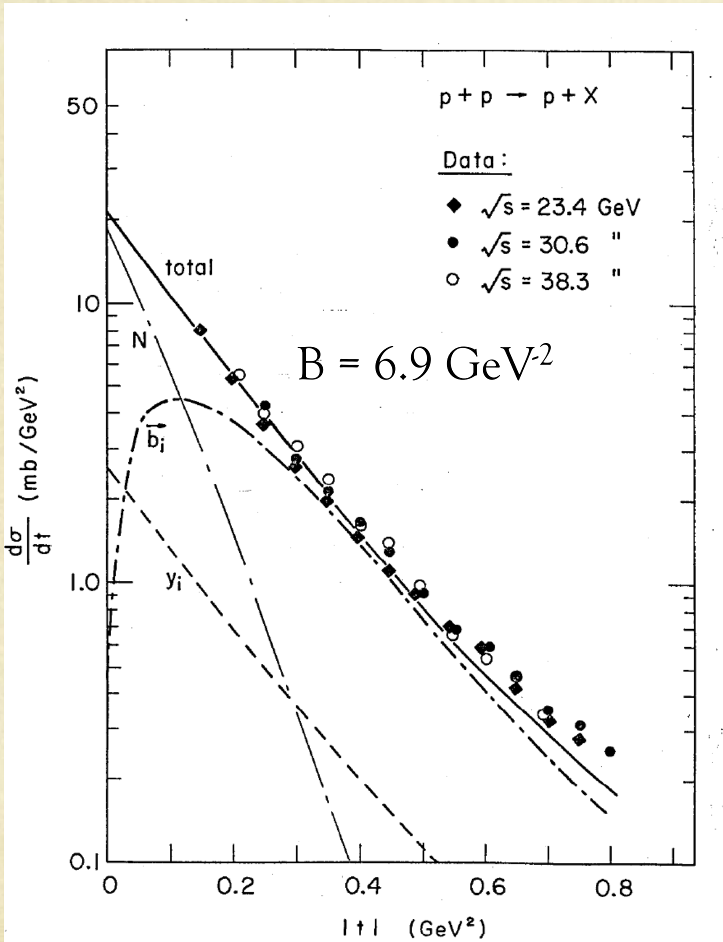
diffraction is peripheral – strongly influenced by unitarity

at $\sqrt{s} \approx 1$TeV and $b \approx 0$,

$\sigma_{el} \approx \frac{1}{2}\, \sigma_{tot} \approx \frac{1}{4}$

$\sigma_{diff}^{inel} \leq 0.01$

DIFFRACTION AT THE ISR ($0.95 < x_F < 1.0$)

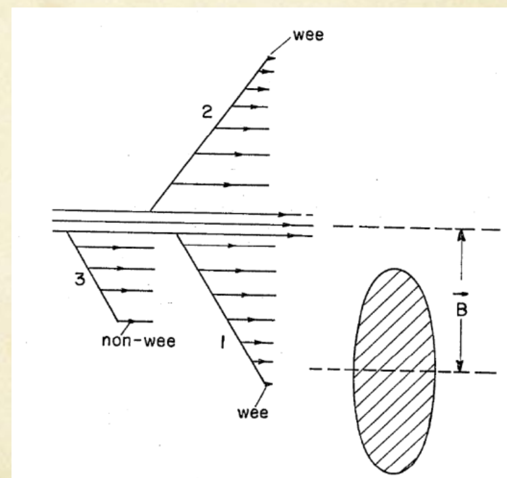


Miettinen & Pumplin, PRD 1978

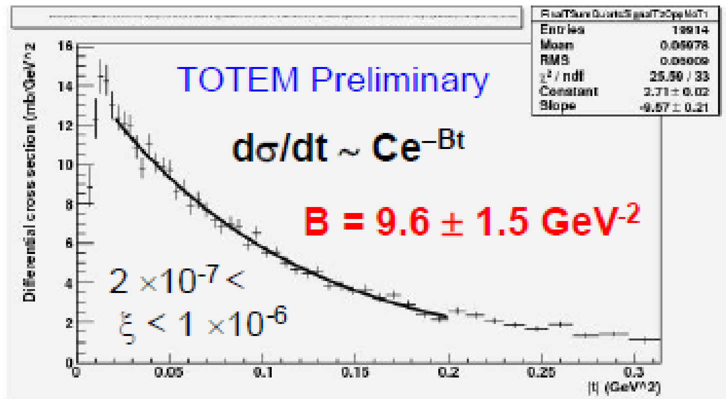
Diffraction due to peripheral interactions;
fluctuations in :

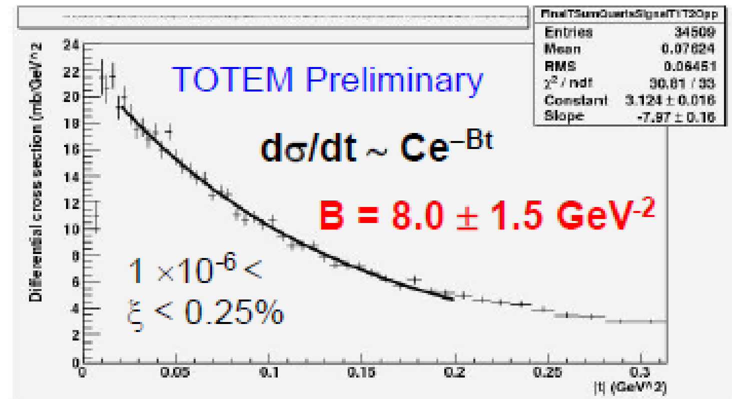
- impact parameter 45%
- number of 45%
- rapidities 10%

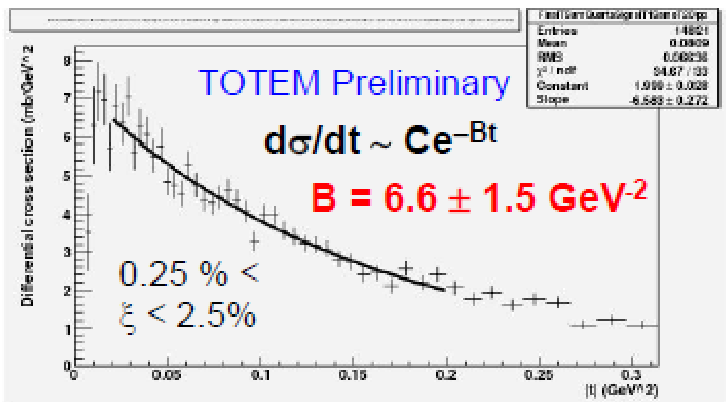
of the wee partons.



SINGLE DIFFRACTION: dσ/dt vs. ξ







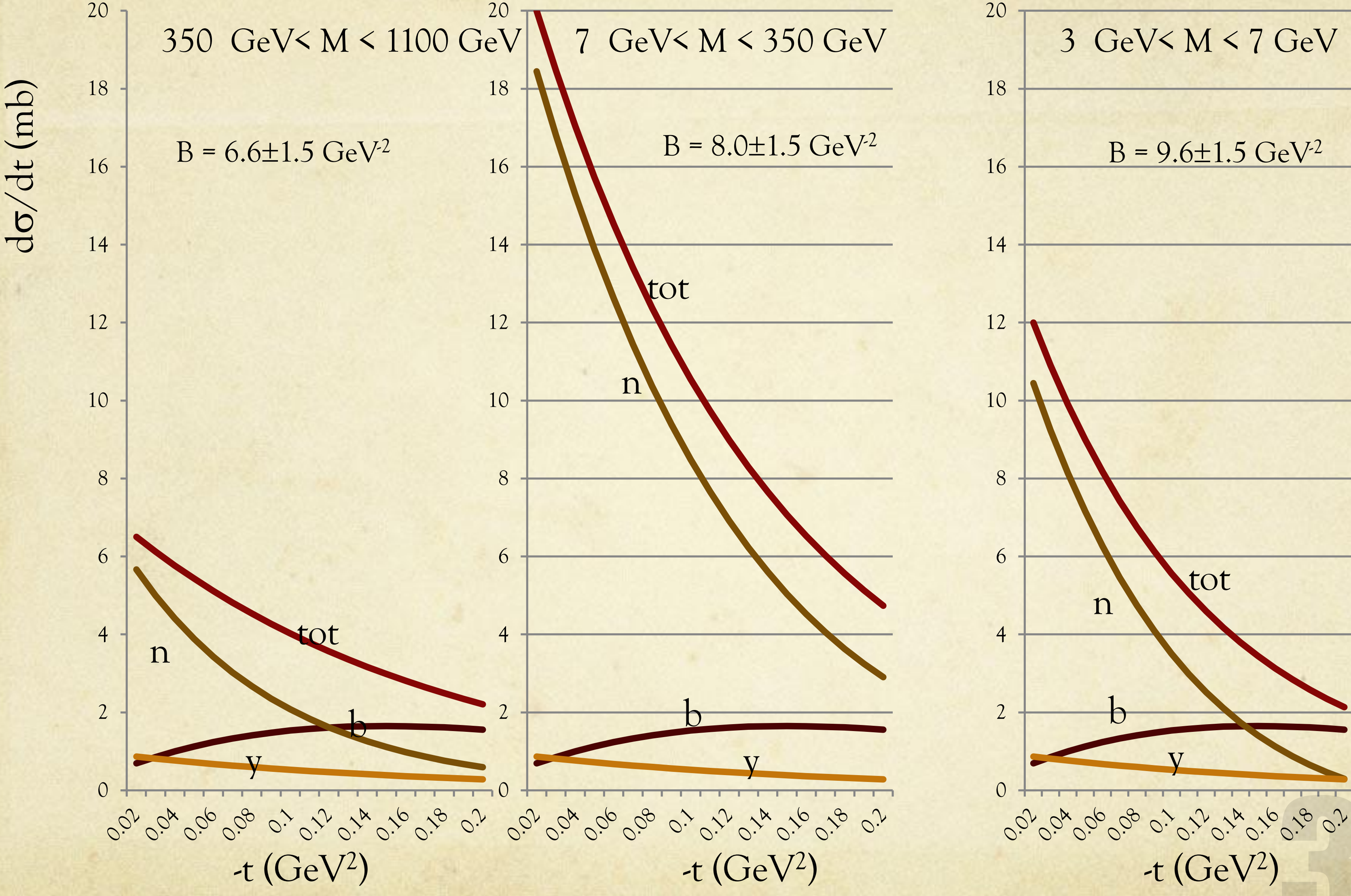
t-distributions still to be corrected for beam divergence & effect of ξ on proton ϕ-acceptance correction

$$\frac{d\sigma_{SD}^{class\ i}}{dt} = e^{-B_i t} - \text{backgr.}$$

$$\sigma_{SD}(\xi > 2\times10^{-7}) = \sum_i \int_0^\infty dt \frac{d\sigma_{SD}^{class\ i}}{dt}$$

Note: There is a minimum value of –t: $|t_{\min}| = \left[(M_X^2 - m_p^2)/2p\right]^2$

DIFFRACTION at LHC vs. Miettinen&Pumplin model



At small diffractive masses (small ξ values), fluctuations in **number of wee states** grows in relative importance vs. b- or y- fluctuations

DIFFRACTIVE CROSS SECTIONS

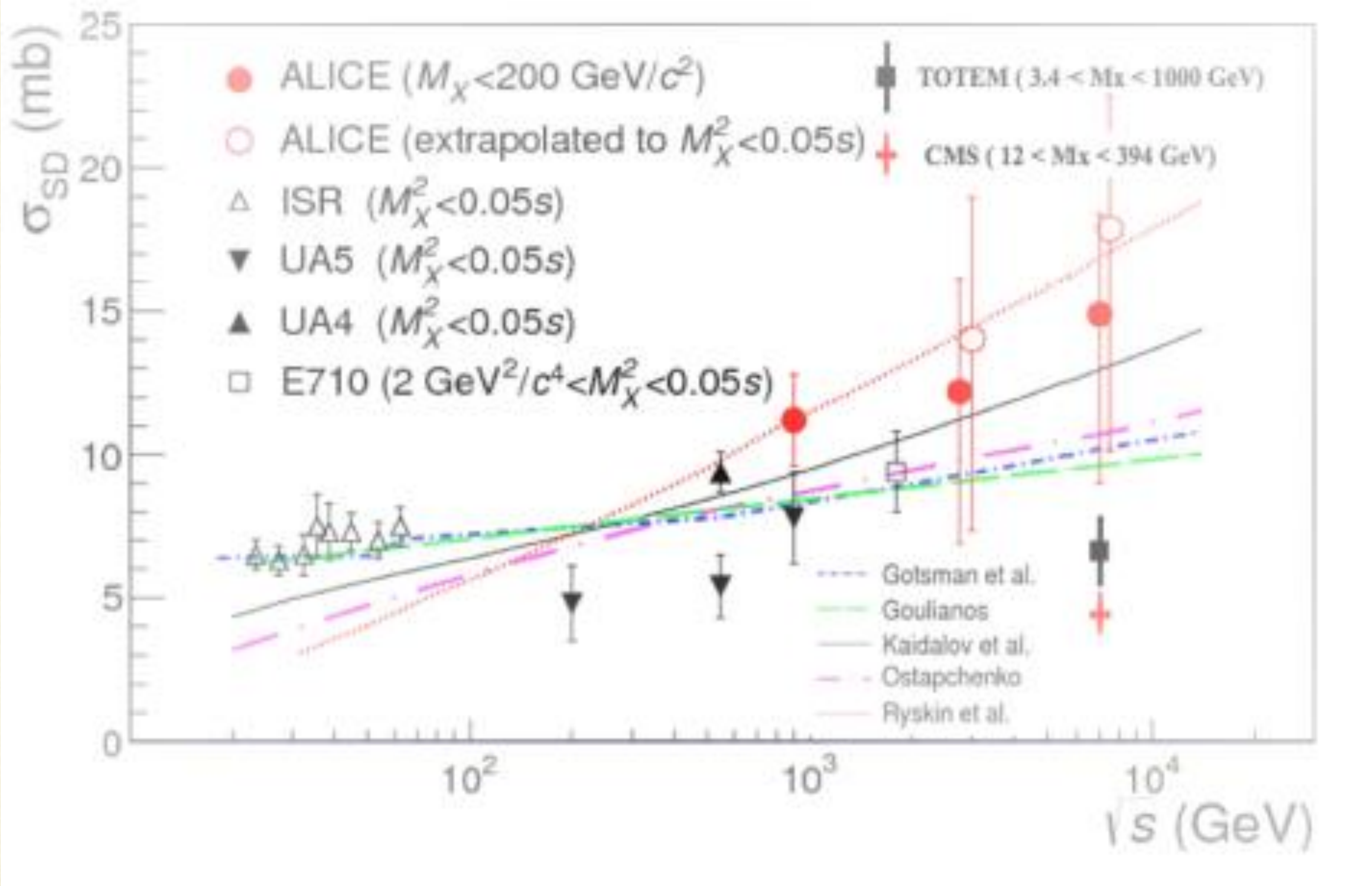
SINGLE DIFFRACTION - SUMMARY

Experiment	Energy TeV	Mass GeV	σ(sd) mb
ALICE	2.76	0-200	$12.2^{+3.9}_{-5.3}$
ALICE	7	0-200	$14.9^{+3.4}_{-5.9}$
CMS	7	12-394	$4.27 \pm 0.04^{+0.65}_{-0.58}$
TOTEM	7	3.4-1100	6.5 ± 1.3
TOTEM	8	3.4-1100	

LOW MASS SINGLE DIFFRACTION - TOTEM

M_{Diff} GeV	<3.4	3.4-1100	3.4-7	7-350	350-1100
TOTEM	2.62±2.17	6.5±1.3	≈1.8	≈3.3	≈1

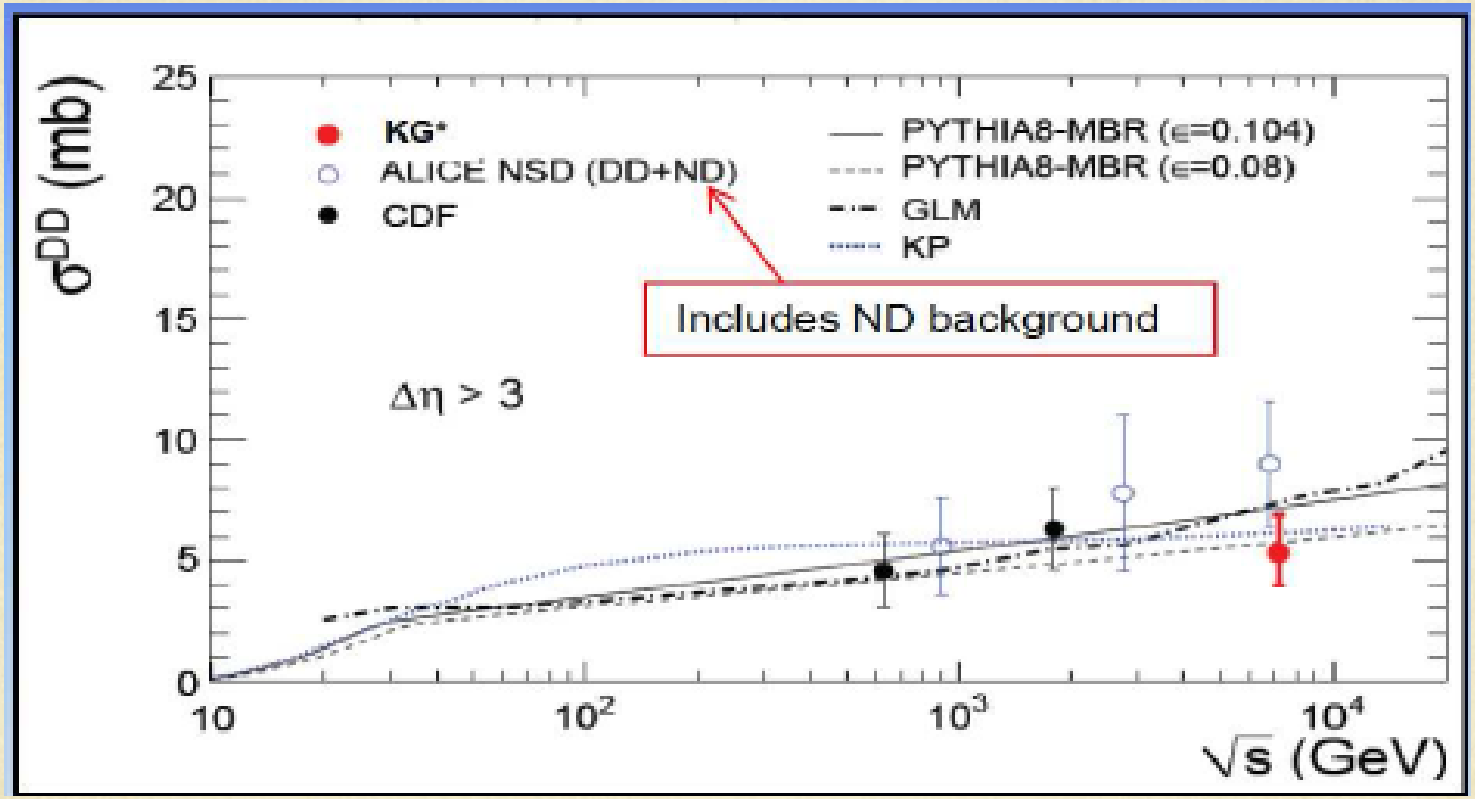
SINGLE DIFFRACTION - SUMMARY



DOUBLE DIFFRACTION - SUMMARY

Experiment	Mass GeV	σ_{dd} mb
ALICE	0-200	9.0 ± 2.6
CMS	$M_{X,Y}>10;\Delta\eta>3$	$0.93 \pm 0.01^{+0.26}_{-0.22}$
TOTEM	$3.4<M_{Diff}<8$	0.116 ± 0.025
PYTHIA 8		0.159
PHOJET		0.101

DOUBLE DIFFRACTION - SUMMARY

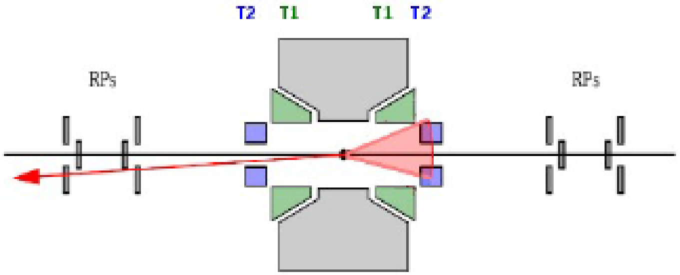


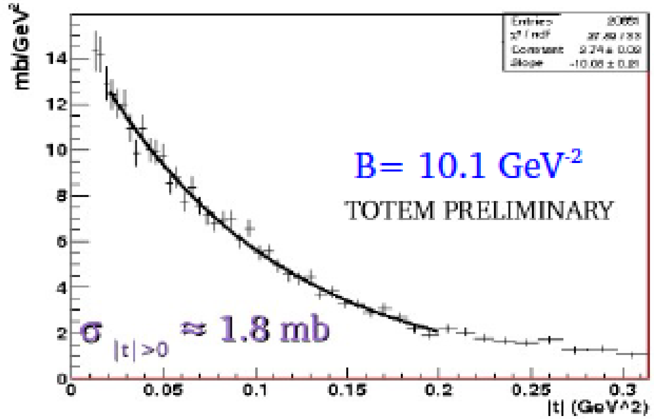
Soft Single Diffractive cross section (7 TeV)

$d\sigma/dt \sim C \cdot e^{-Bt}$

Low Mass

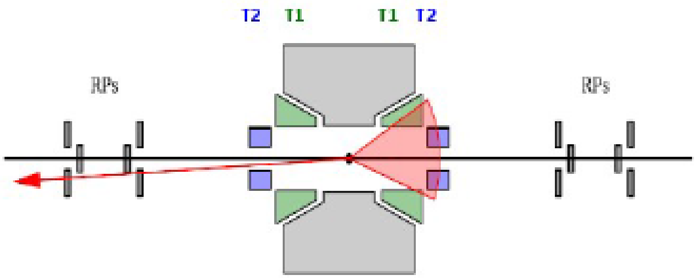
M=3.4 - 8 GeV

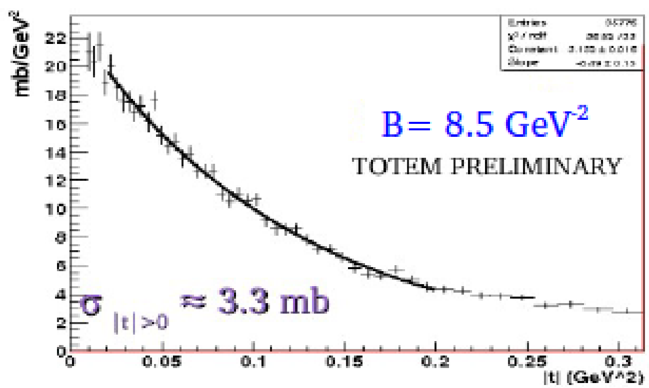




Medium Mass

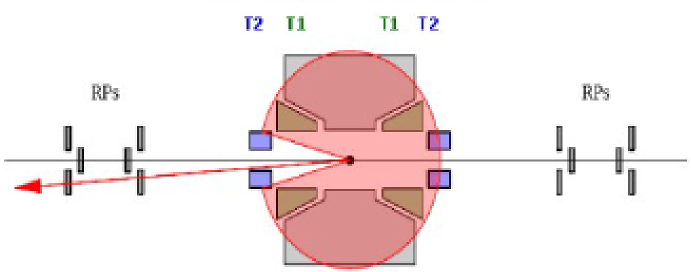
M=8 - 350 GeV

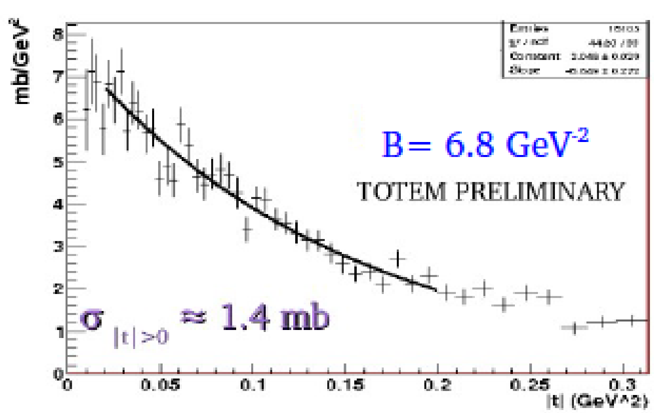




High Mass

M=0.35 - 1.1 TeV





Corrections include:
- Trigger efficiency
- Reconstruction efficiency
- Proton acceptance
- Background subtraction
- Extrapolation to t=0

Missing corrections:
- Class migrations
- Effects due to resolutions and beam divergence

- Estimated uncertainties: B~15% σ~20%

Preliminary:
$\sigma_{SD} = 6.5 \pm 1.3$ mb
($3.4 < M_{SD} < 1100$ GeV)

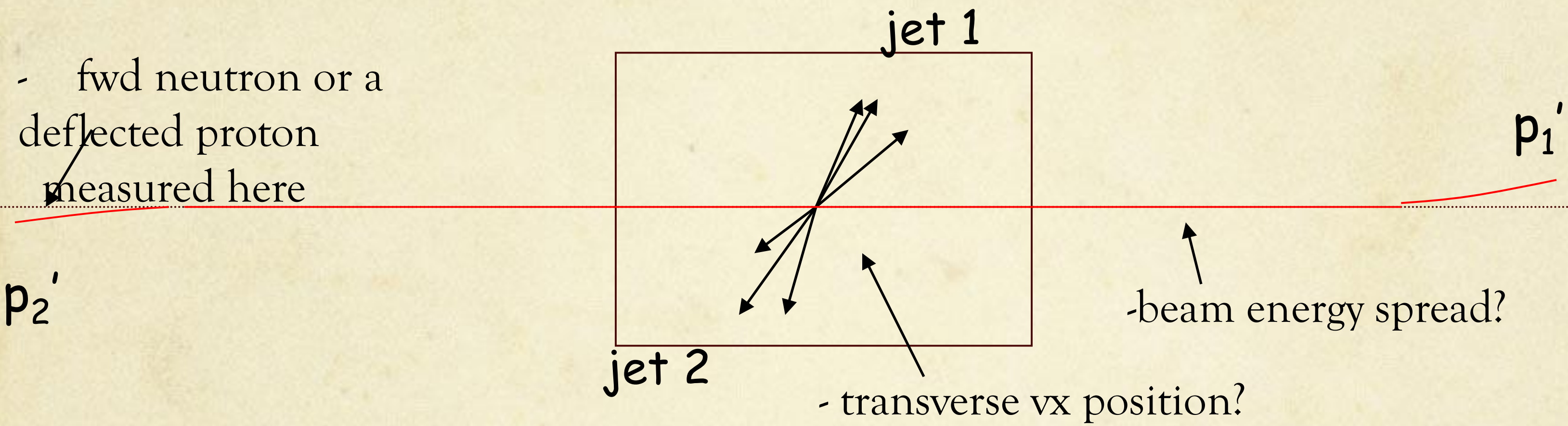
Very high masses measurement ongoing

CENTRAL EXCLUSIVE PRODUCTION

MASS X IN $p_1 p_2 \rightarrow p_1' + X + p_1'$ MEASURED AS:

- fwd neutron or a deflected proton measured here

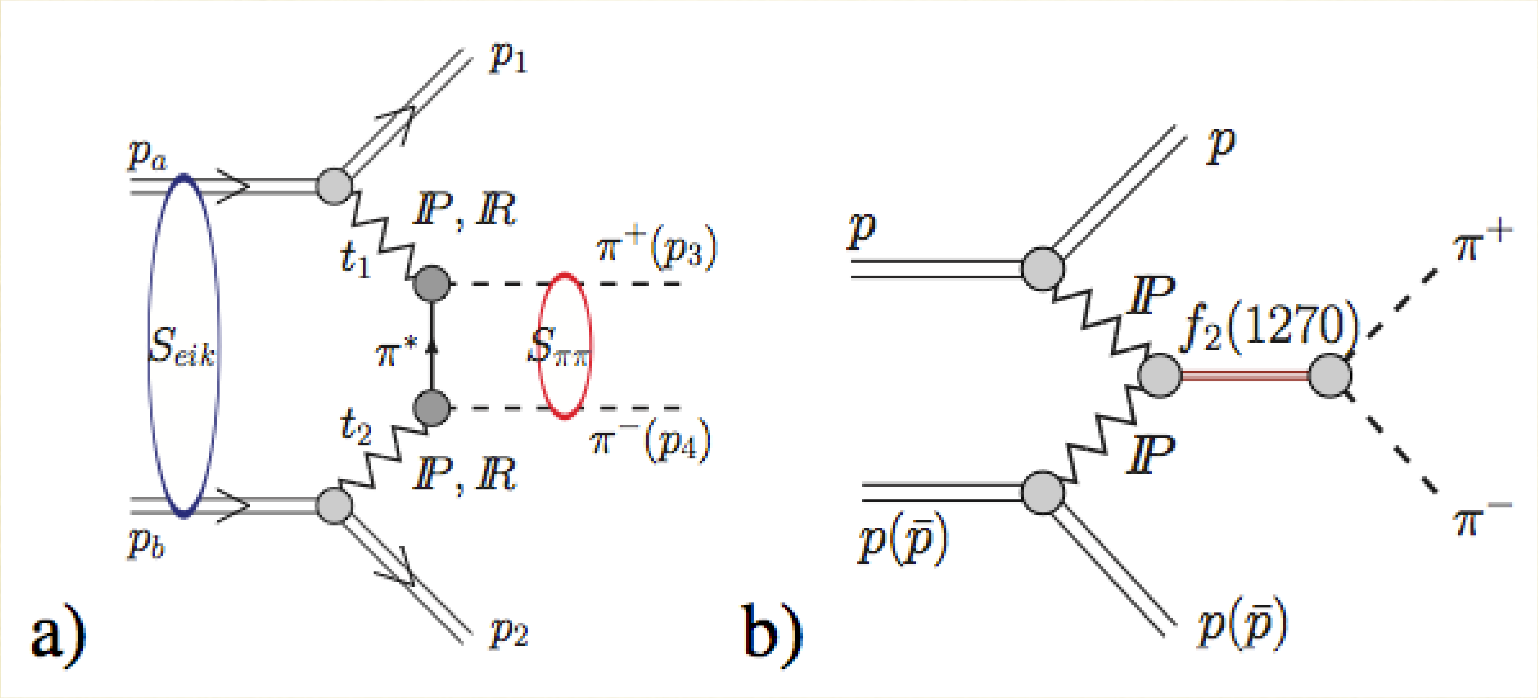
$$M_X^2 = (p_1 + p_2 - p_1' - p_2')^2$$



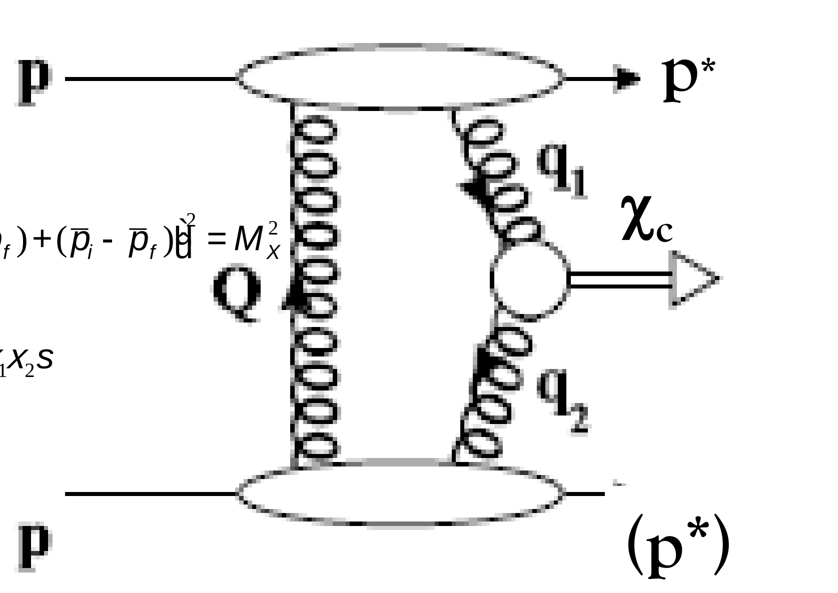
- leading neutrons or protons on both sides

- a central system separated by rap gaps

SOFT CENTRAL DIFFRACTION



HARD CENTRAL EXCLUSIVE PRODUCTION



$$\left[(p_i - p_f) + (\bar{p}_i - \bar{p}_f)\right]^2 = M_X^2$$

$$M_X^2 = x_1 x_2 s$$

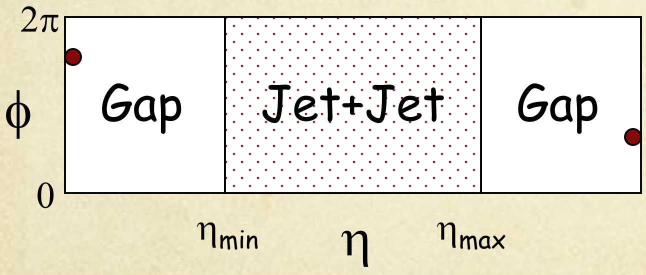
CEP transforms LHC into a gluon factory, 1/3000 pure gluon jets

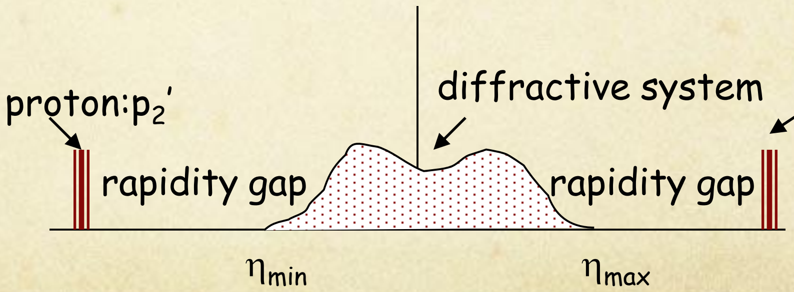
$J^{PC} = 0^{++},..$

Measure the parity $P = (-1)^J$: $d\sigma/d\varphi \propto 1 + \cos 2\varphi$

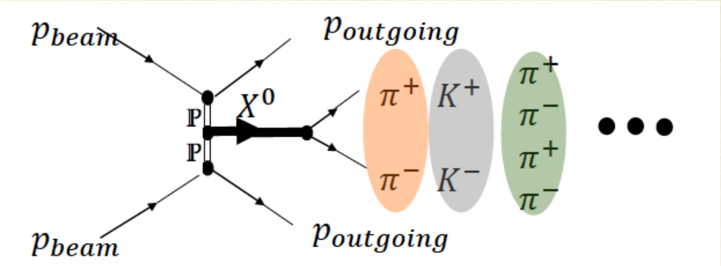
Is well identified whenever forward rapidities are well covered – ADs&ZDCs – and **pile-up** is under control – $L \leq 10^{30}\ cm^{-2}s^{-1}$

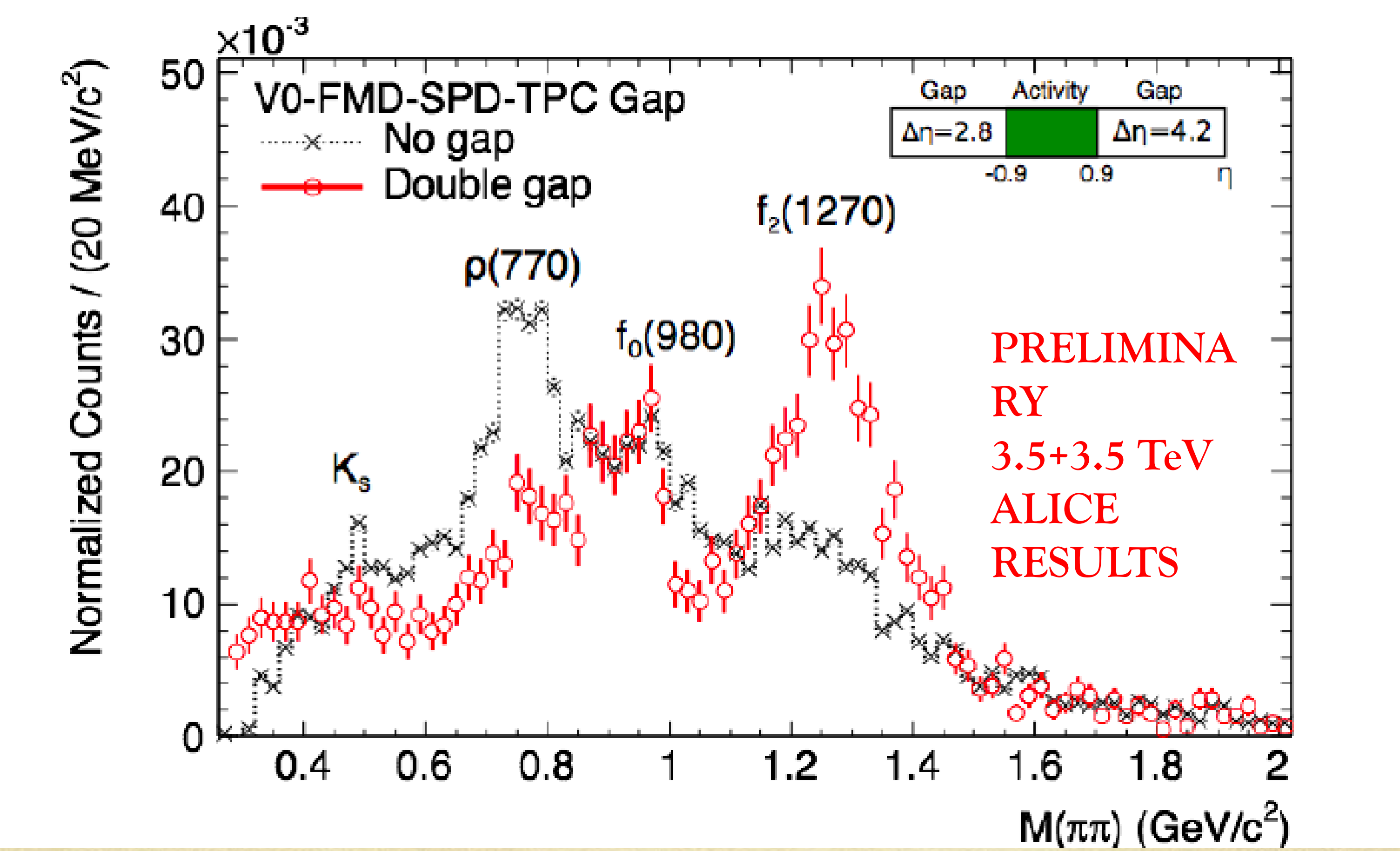
ALICE event rates ~ 200 kHz ⇒ large statistics during the nominal LHC runs





CENTRAL ππ MASS: EXCLUSIVE vs. INCLUSIVE





PRELIMINARY
3.5+3.5 TeV
ALICE RESULTS

DINO's GLUEBALL?

Saturation glueball?

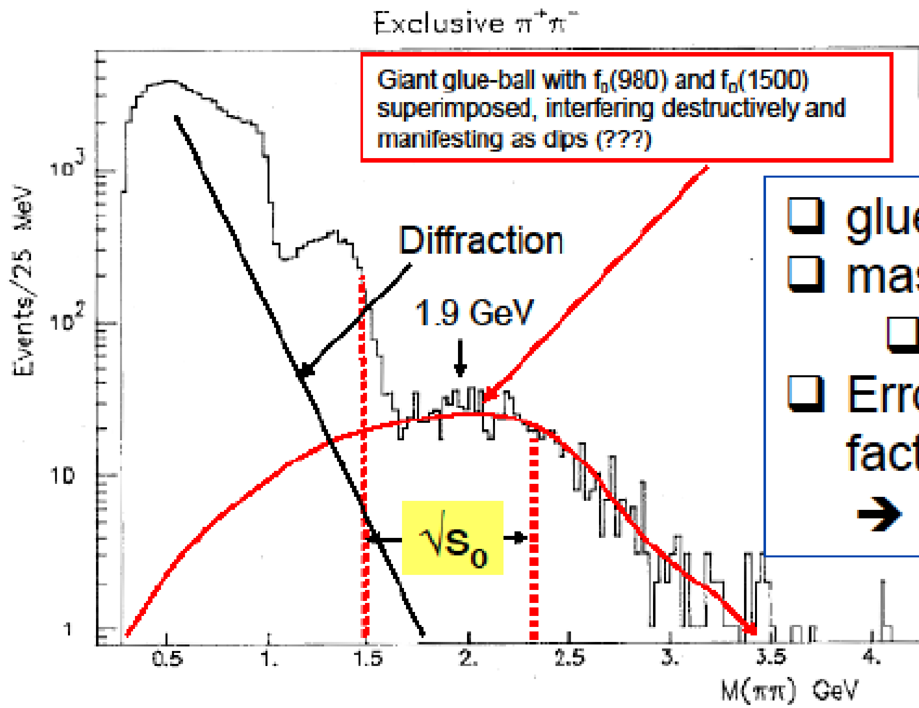
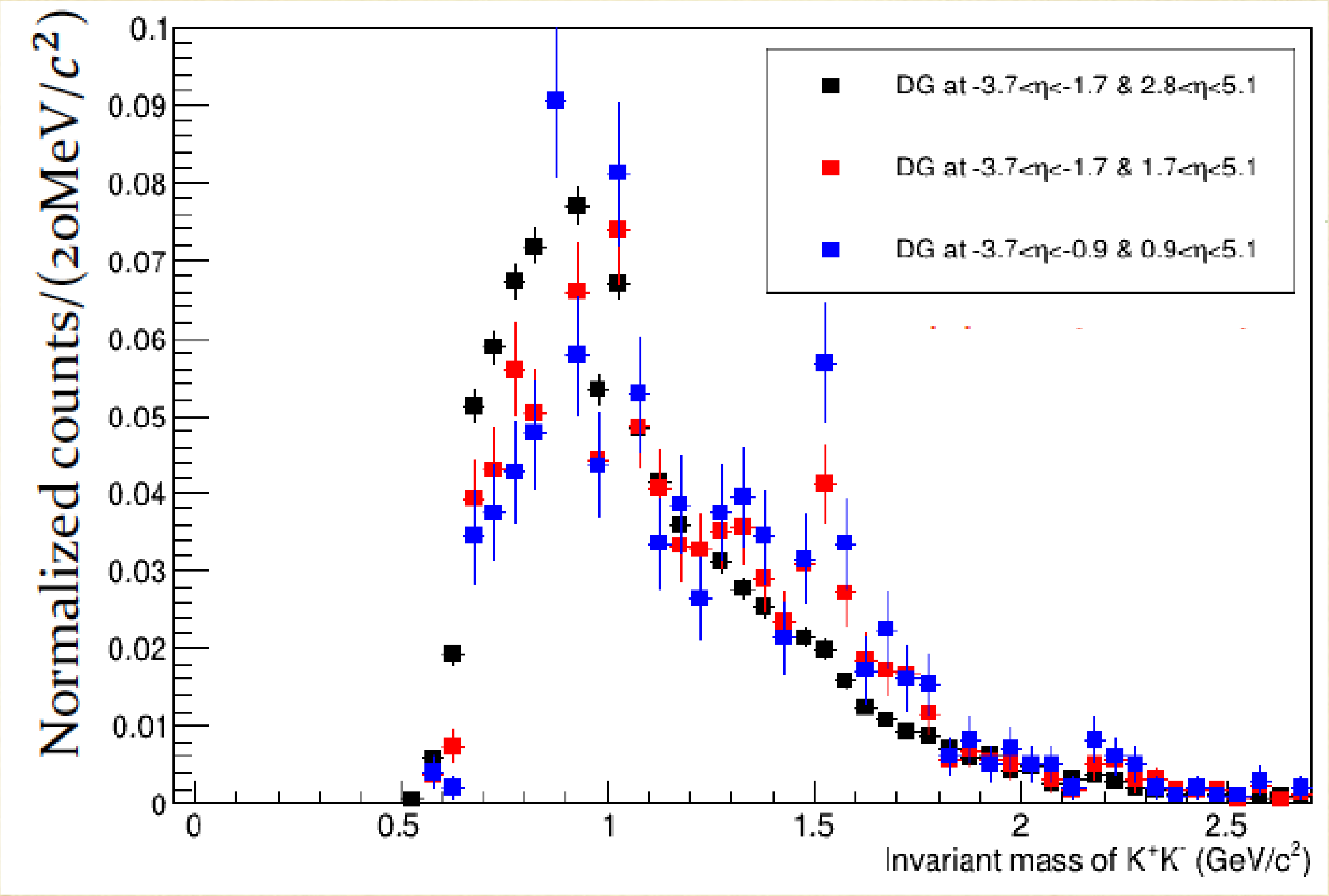


Figure 8: $M_{\pi^+\pi^-}$ spectrum in *DPE* at the ISR (Axial Field Spectrometer, R807 [97, 98]). Figure from Ref. [98]. **See M.G.Albrow, T.D. Goughlin, J.R. Forshaw, hep-ph>arXiv:1006.1289**

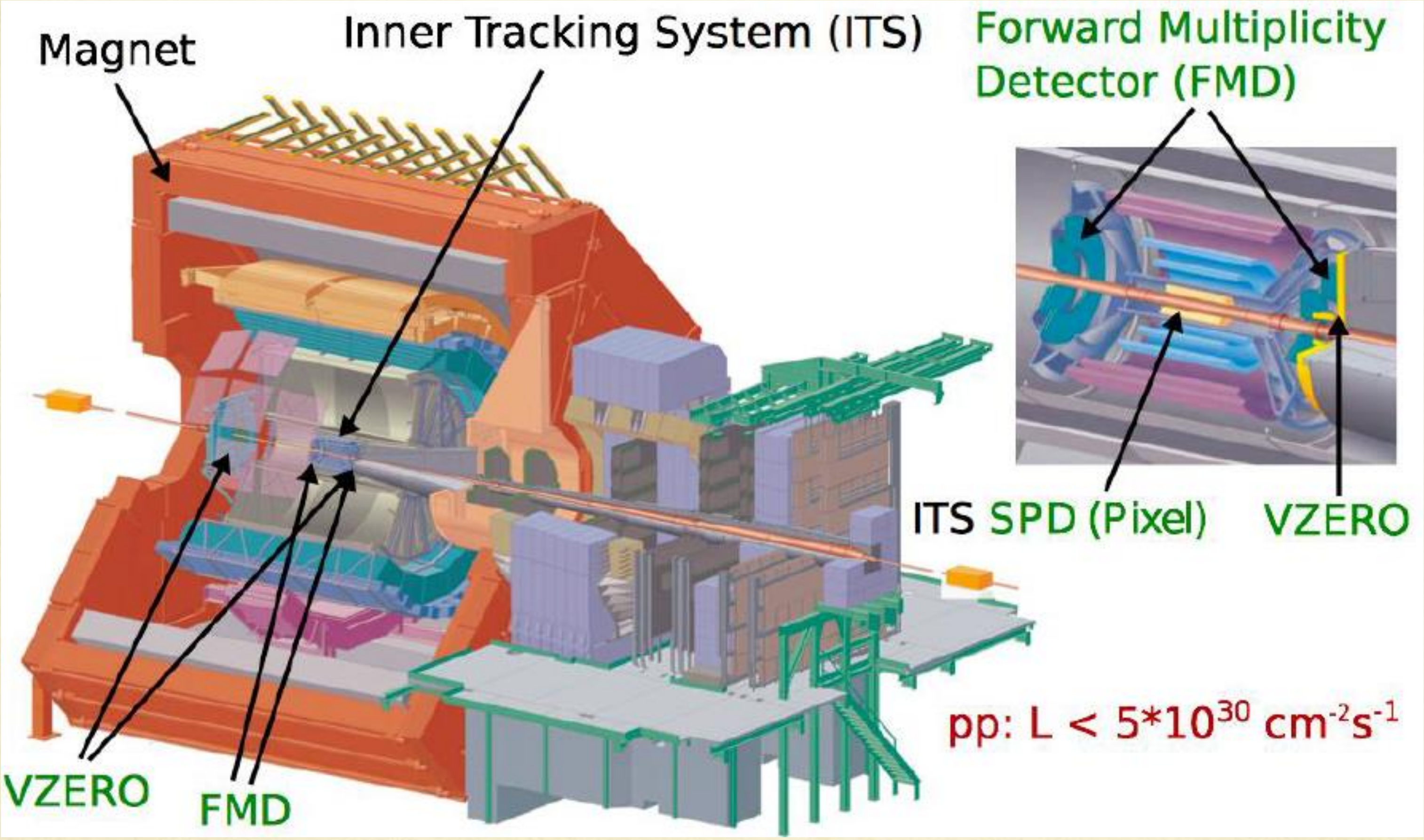
- ❑ glue-ball-like object ➔ "superball"
- ❑ mass →1.9 GeV ➔ m_s^2= 3.7 GeV
  - ❑ agrees with RENORM s_o=3.7
- ❑ Error in s_0 can be reduced by factor ~4 from a fit to these data!

➔ reduces error in σ_t.

CENTRAL K^+K^- MASS vs. RAP GAP SELECTION - PRELIMINARY!



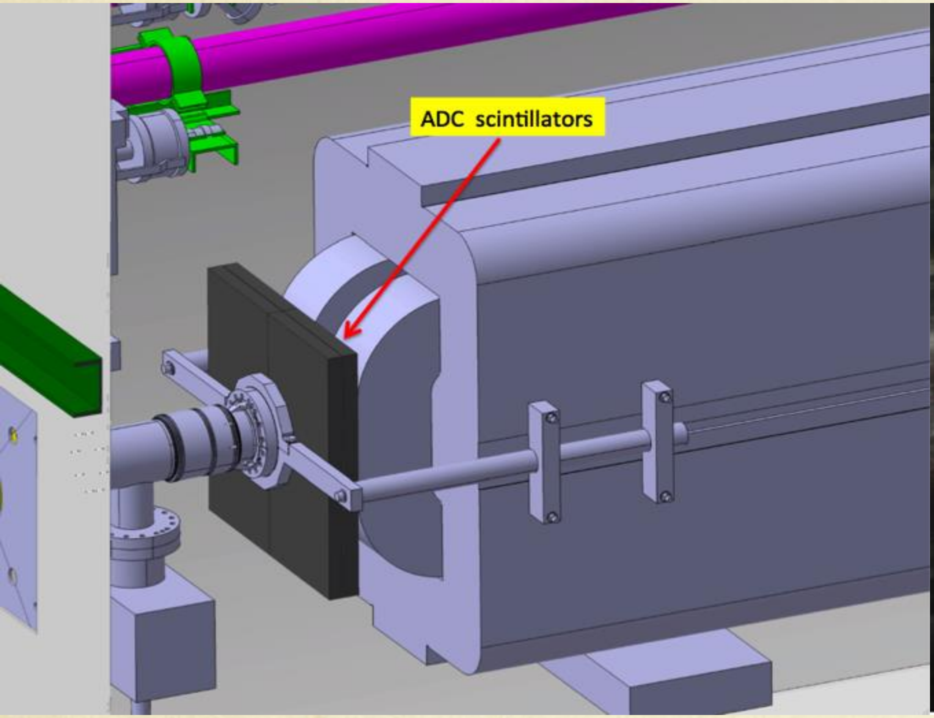
ALICE FORWARD DETECTORS

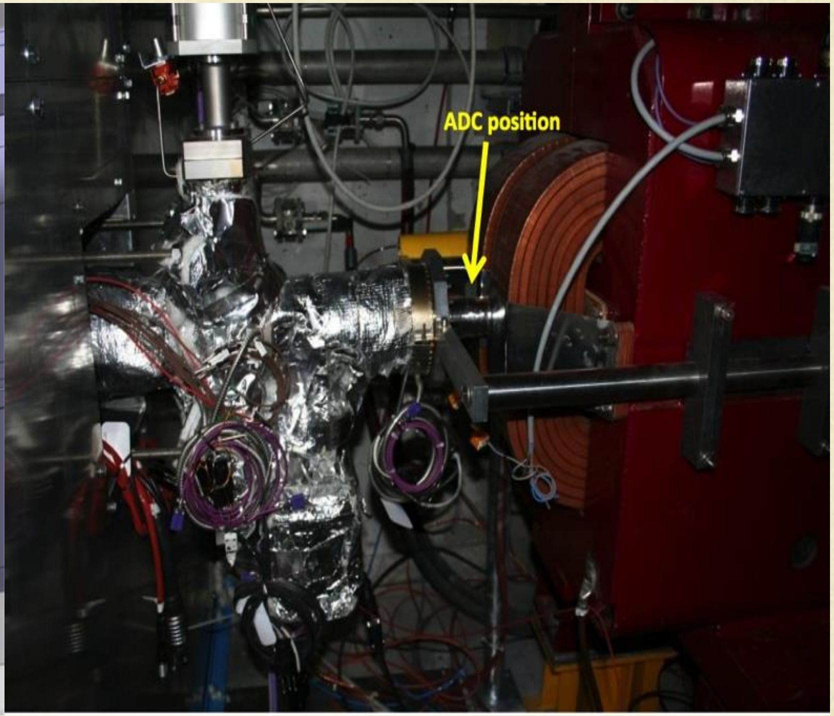


ADA/ADC UPGRADE FOR IMPROVED FORWARD COVERAGE: 8 + 8 PMD QUADRANTS AT BOTH SIDES OF THE EXPERIMENT – **MEXICAN GROUPS IN KEY ROLES**

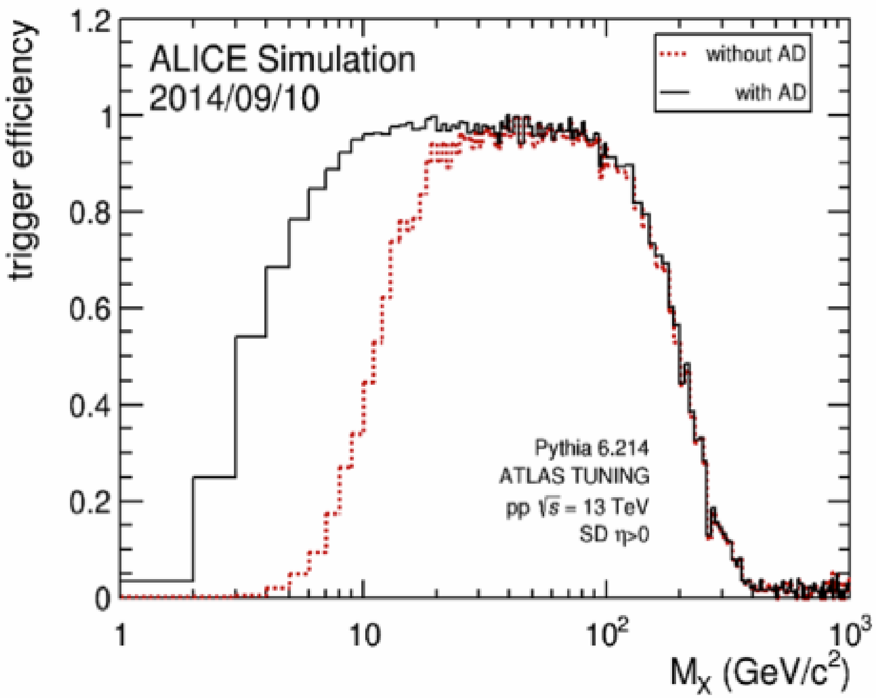
Gerardo, Arturo, Mari Rodriguez, Ildefonso..

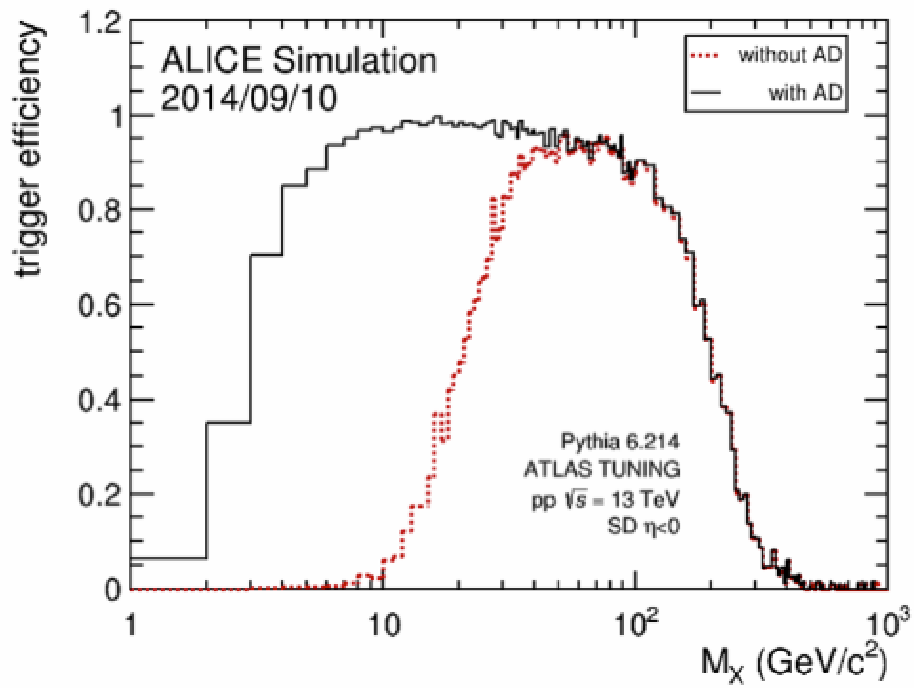
ADC/ADA DETECTORS INSTALLED ON BOTH SIDES OF THE ALICE INTERACTION POINT





ADC FORWARD TRIGGER EFFICIENCY

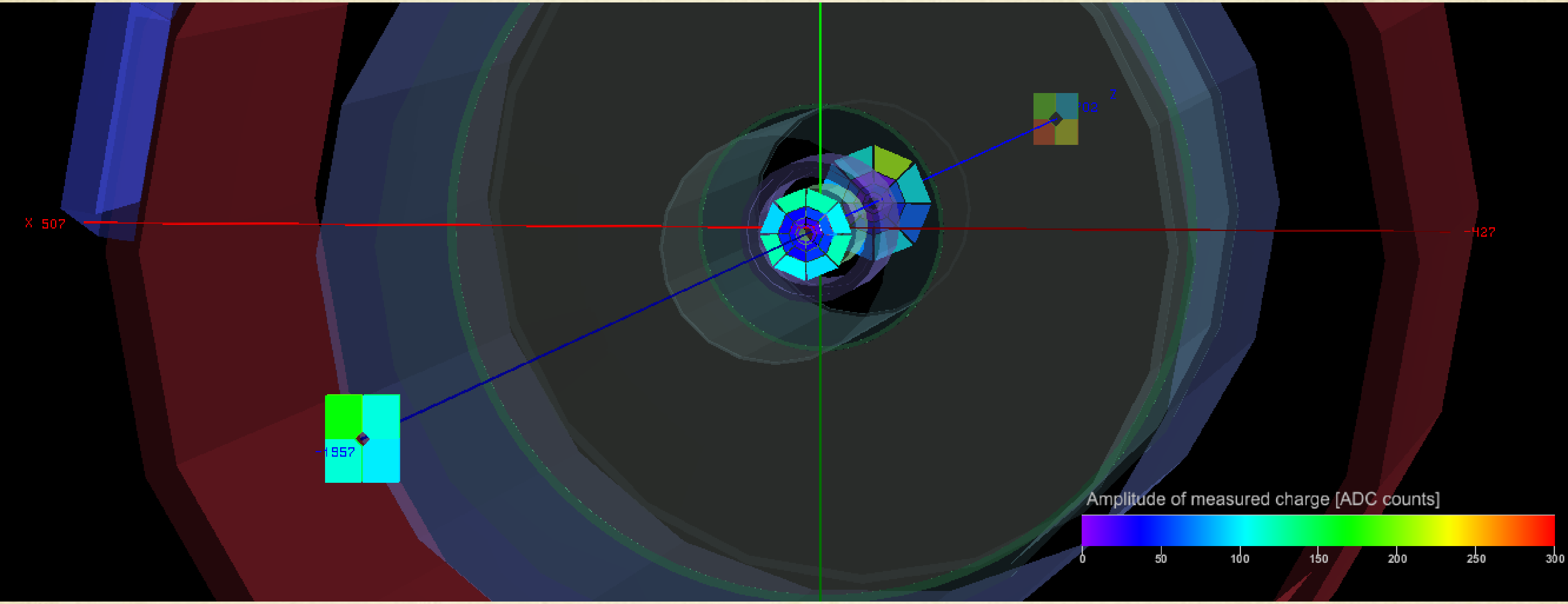




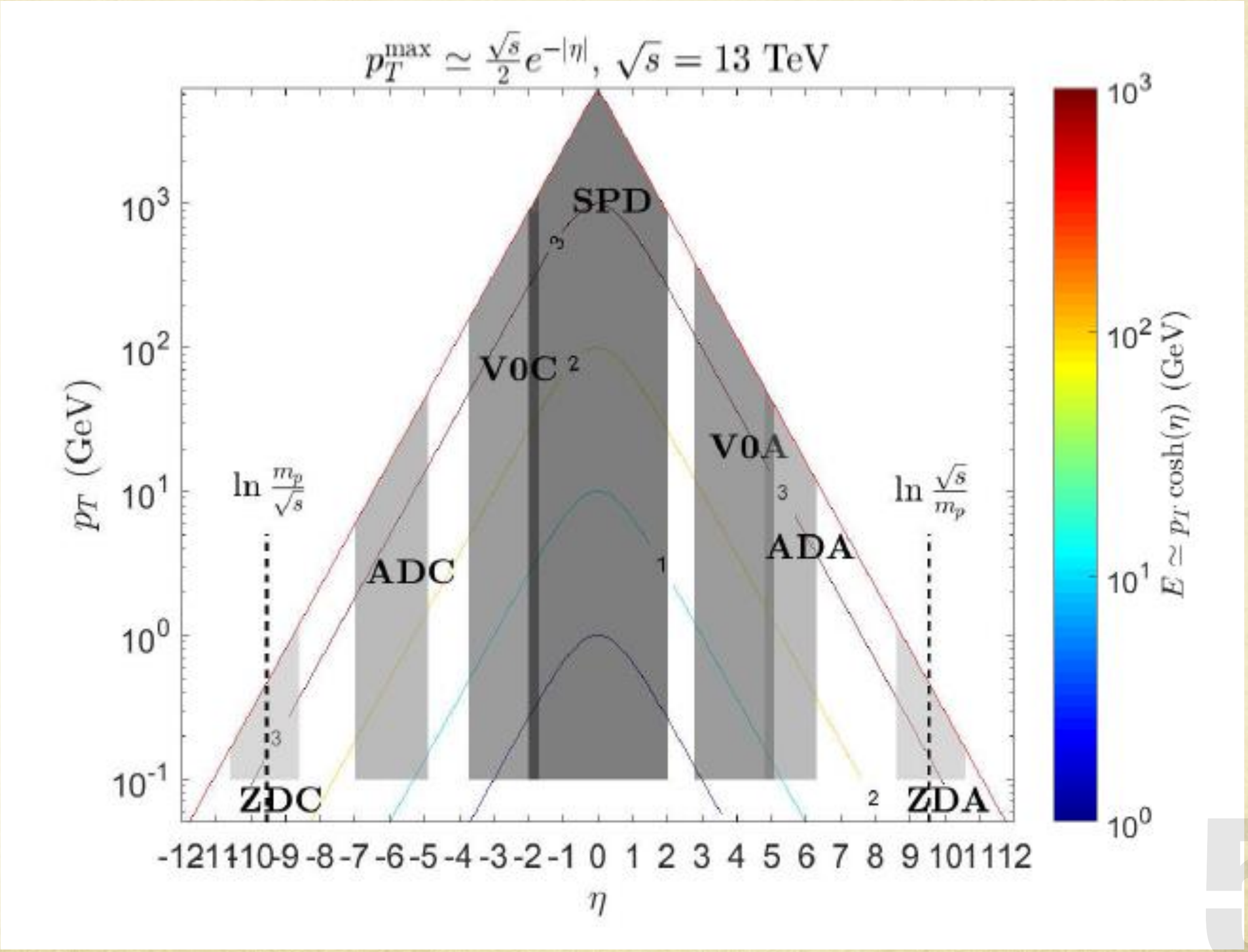
50% acceptance at 3 GeV

efficiency down to lowest N* masses

A SPLASH EVENT

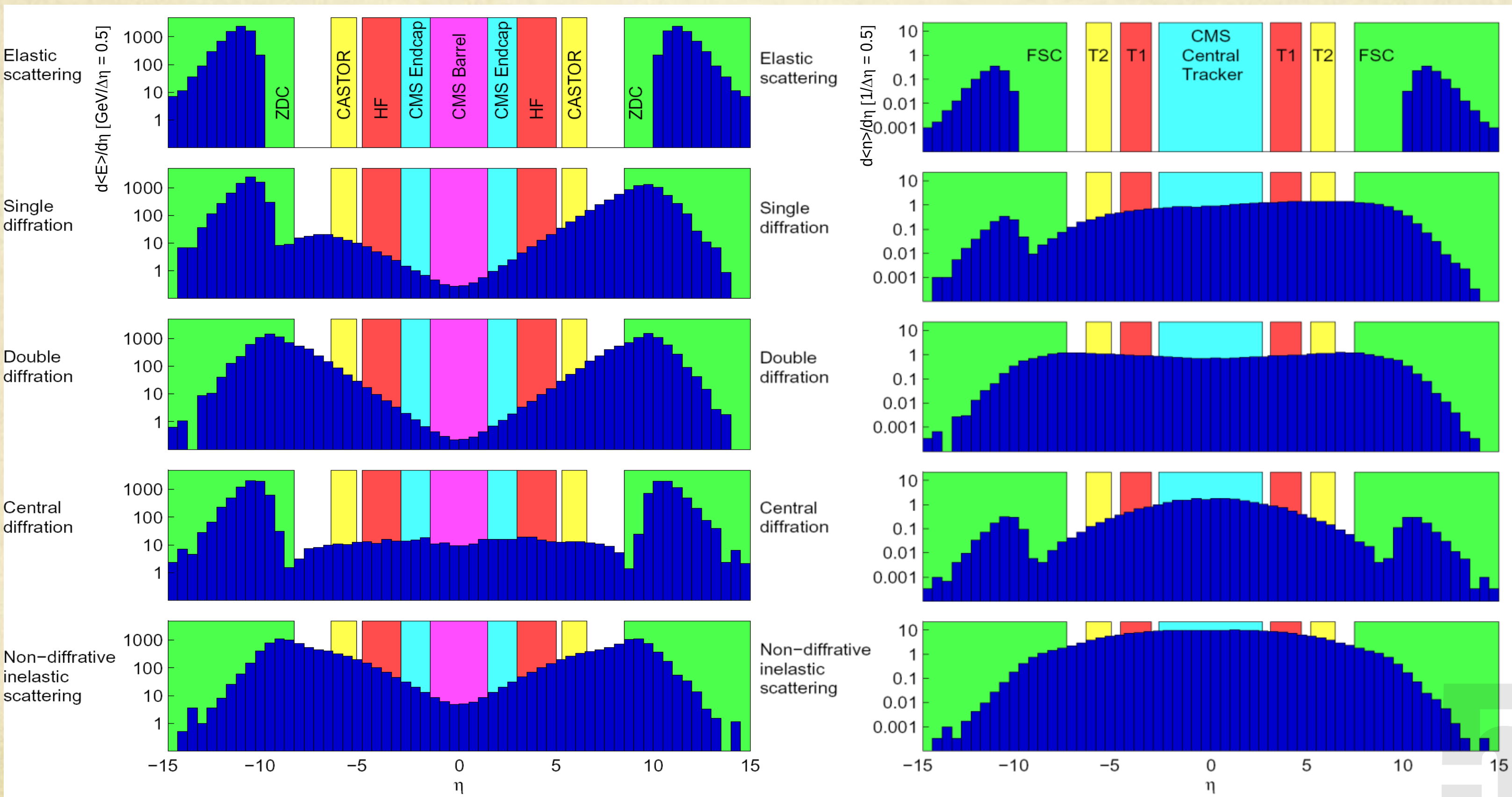


p_T-η ACCEPTANCE



DEVELOPMENT IN ANALYSIS TECHNIQUES OF DIFFRACTION

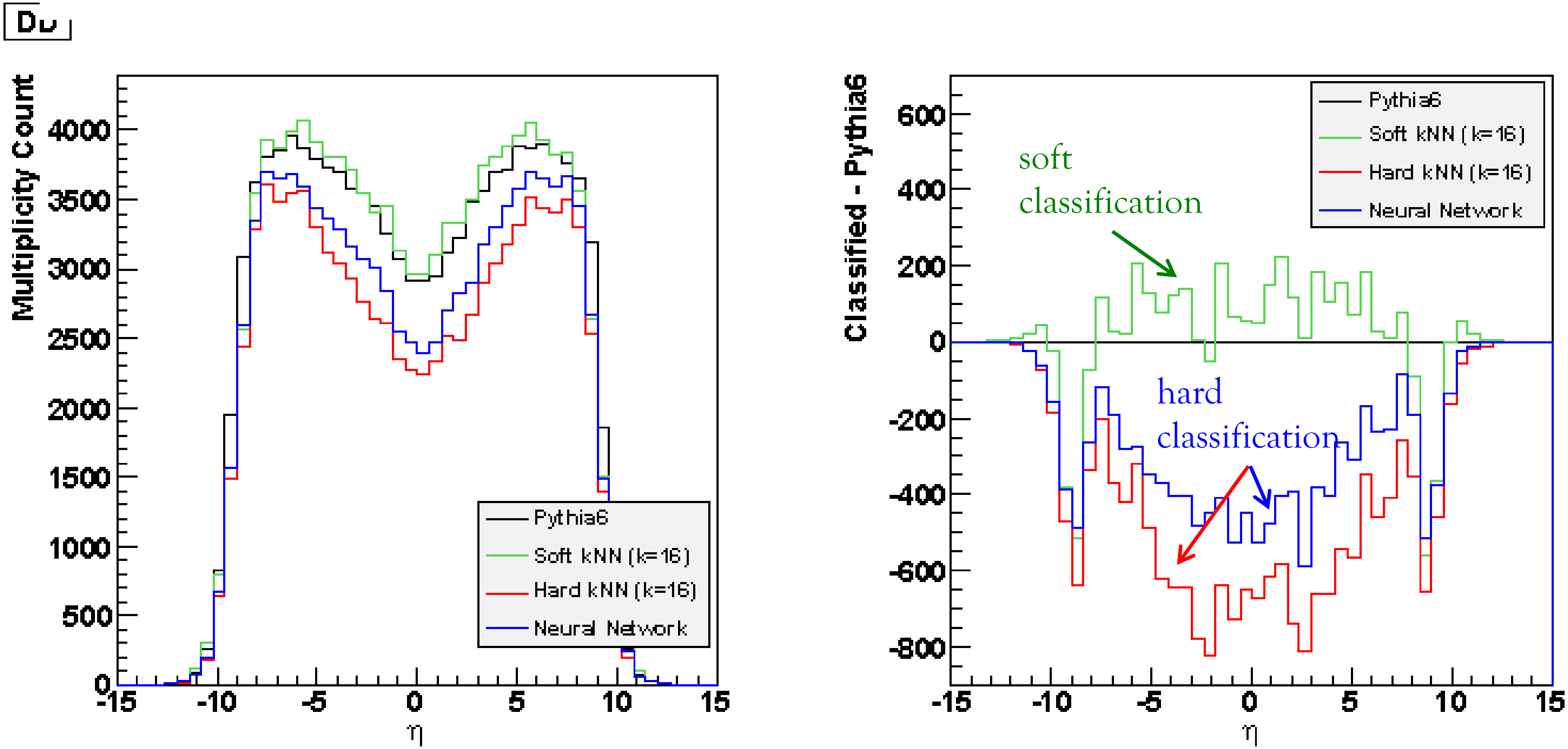
ENERGIES MULTIPLICITIES



'soft' Quantum Mechanics compatible classification of diffractive event classes

see: **Multivariate Techniques for Identifying Diffractive Interactions at the LHC**, RO with Kuusela et al., **Int.J.Mod.Phys. A25 (2010) 1615-1647**

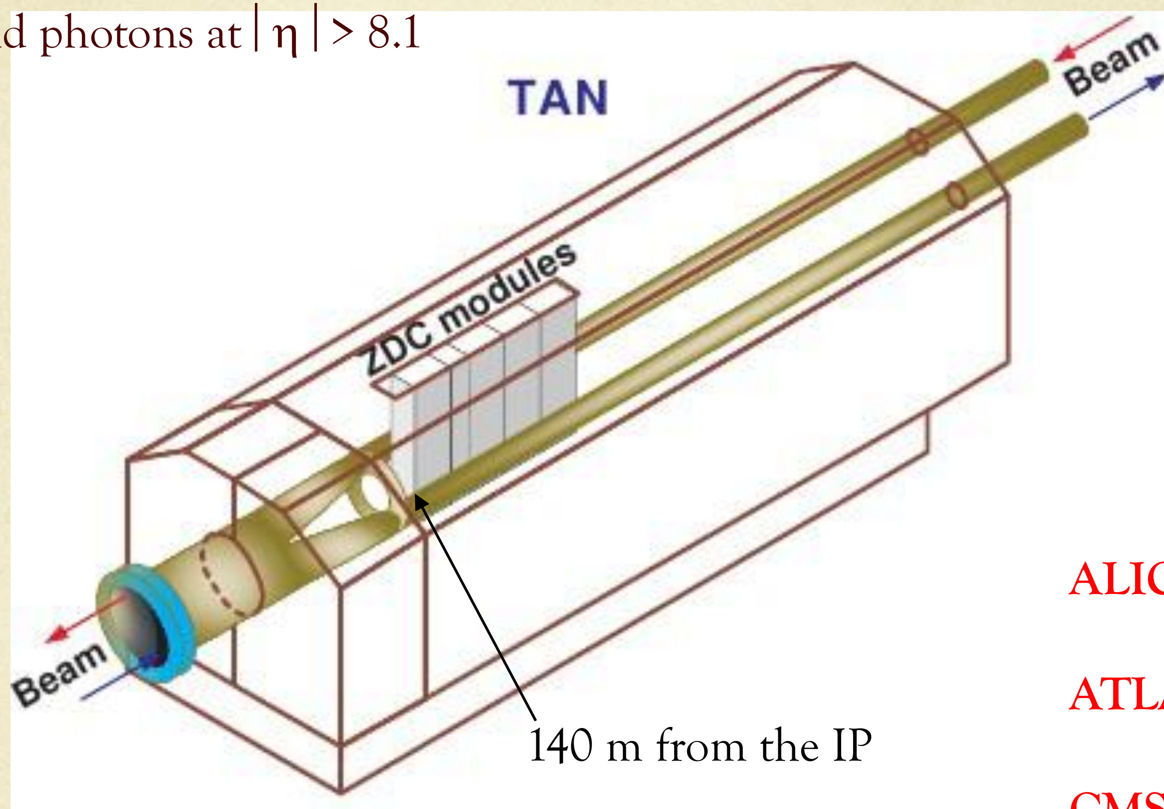
INCLUSIVE DISTRIBUTIONS ARE OBTAINED BY USING THE CLASS PROBABILITIES AS WEIGHTS



Charged particle multiplicities plotted for Double Diffractive Pythia 6 MC events vs. pseudorapidity (left). The DD events are identified event by event by using either "soft" or "hard" classification, then compared with the MC truth (right). Soft event classification performs adequately – hard classification does not.

Zero Degree Calorimeter - ZDC

Quartz fiber Tungsten sampling calorimeter
for neutrons and photons at $|\eta| > 8.1$



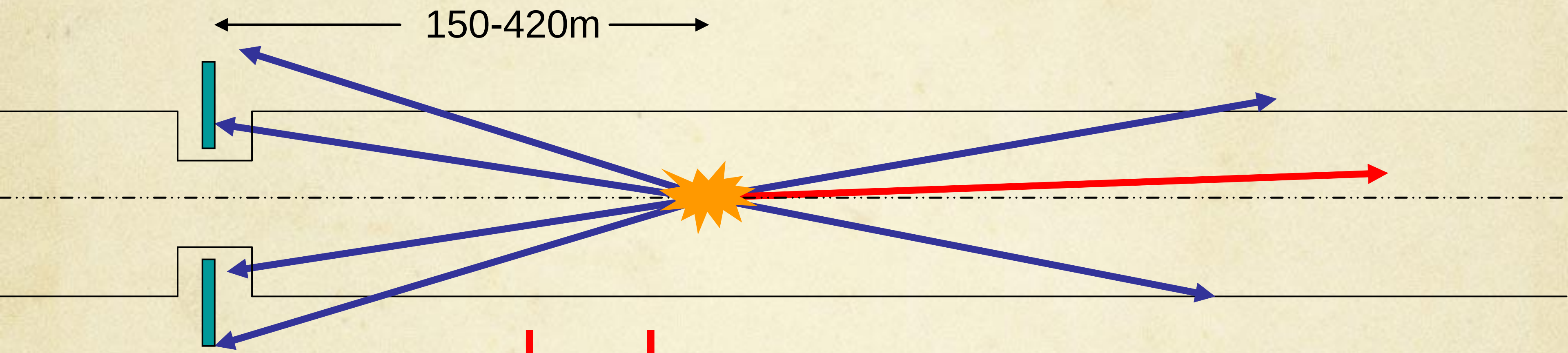
ALICE

ATLAS/LHCf

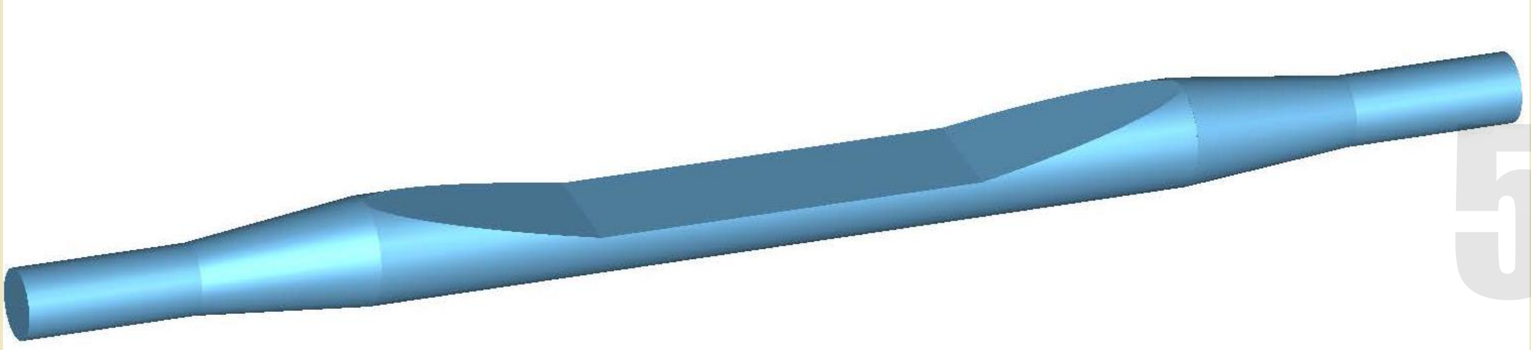
CMS/TOTEM

Reconstruction of π^0, η, η', Δ, Σ, Λ

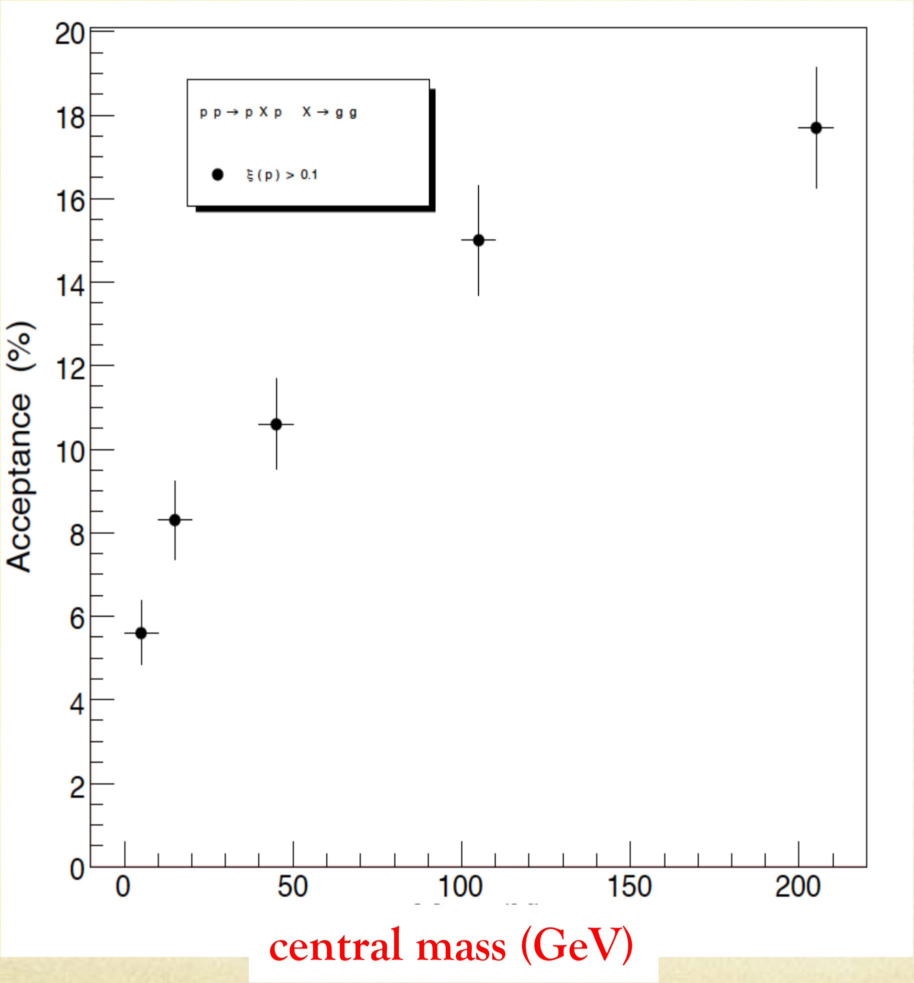
Forward – Very Forward – Particle Detection at the LHC (2): Go into the Beam Pipe (or Move It!)



$|\eta| > 7$

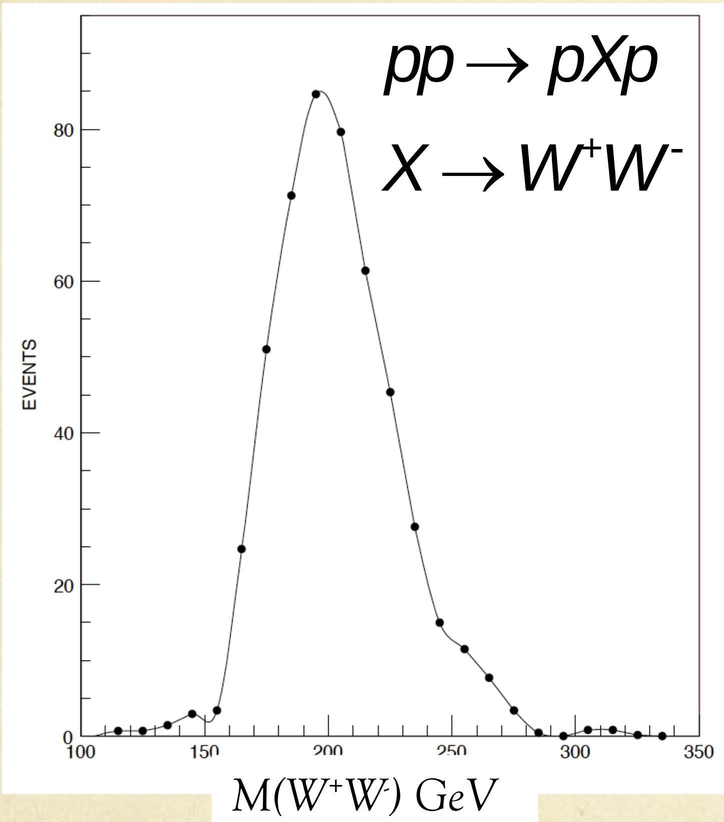


CENTRAL MASS ACCEPTANCE

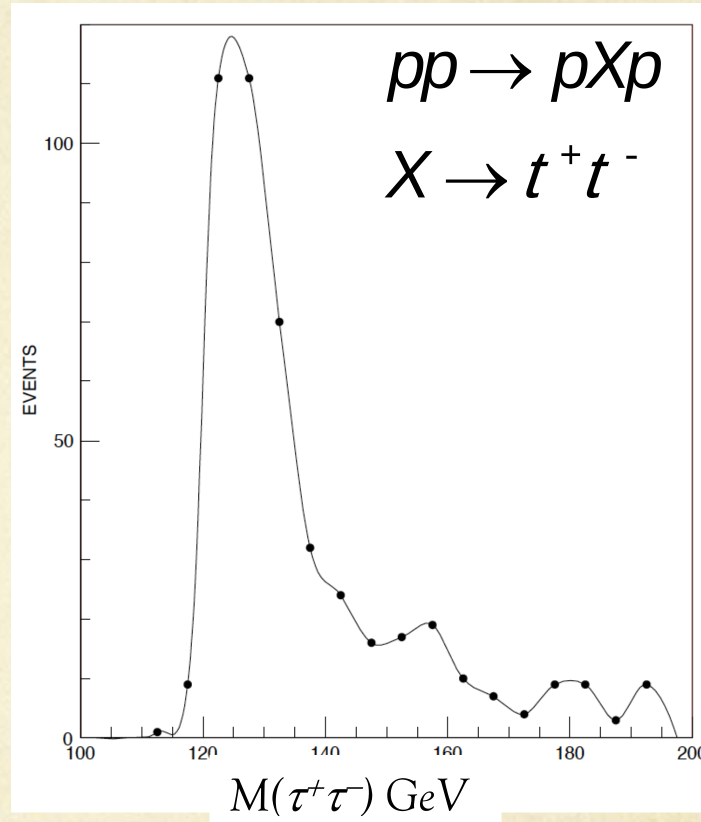


CENTRAL MASS RESOLUTION FOR THE 'POCKET DETECTORS'; PROTON $\xi > 0.1$

M = 200 GeV σ =23 GeV

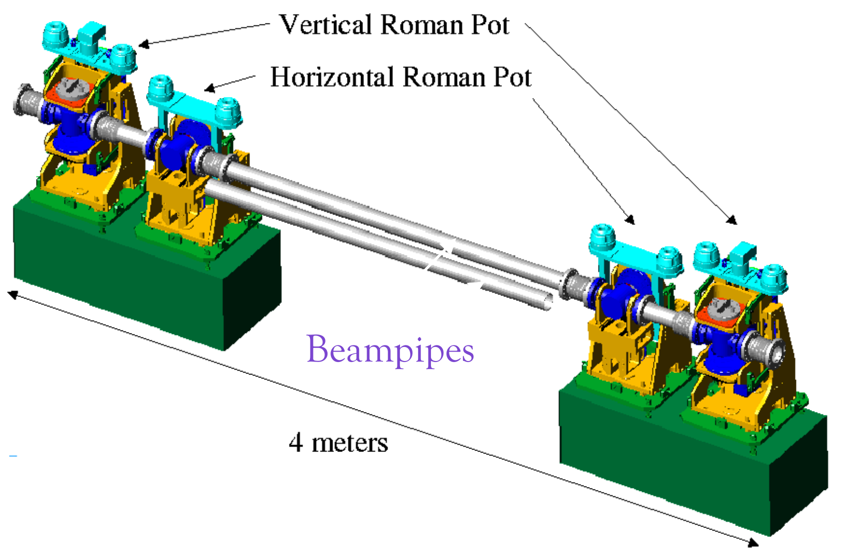


M = 125 GeV σ =13 GeV



NOTE: $\tau \rightarrow \mu\nu\nu$, the mass resolution is improved by a 0C fit constraint: 7000 GeV = $\Sigma p_z = p_z(\tau^+) + p_z(\tau) + p_z(p)$.
For $\xi > 0.08$, ε = 15%. Simulation results by Jerry W. Lämsä.

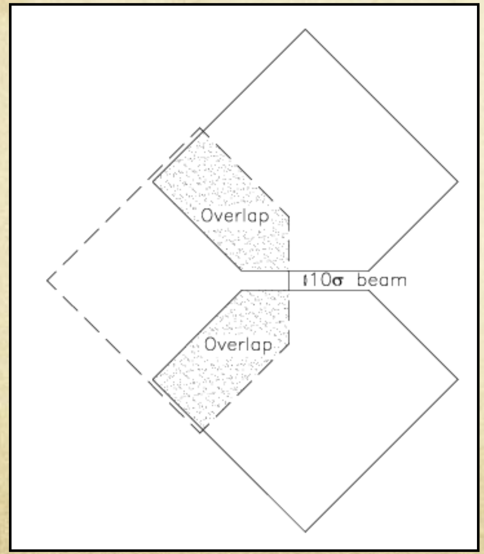
roman pots v1.0



fwd protons with a few μrad angles: detection at 10σ + d from the beam (σ_{beam} ~ 80μm at RP)

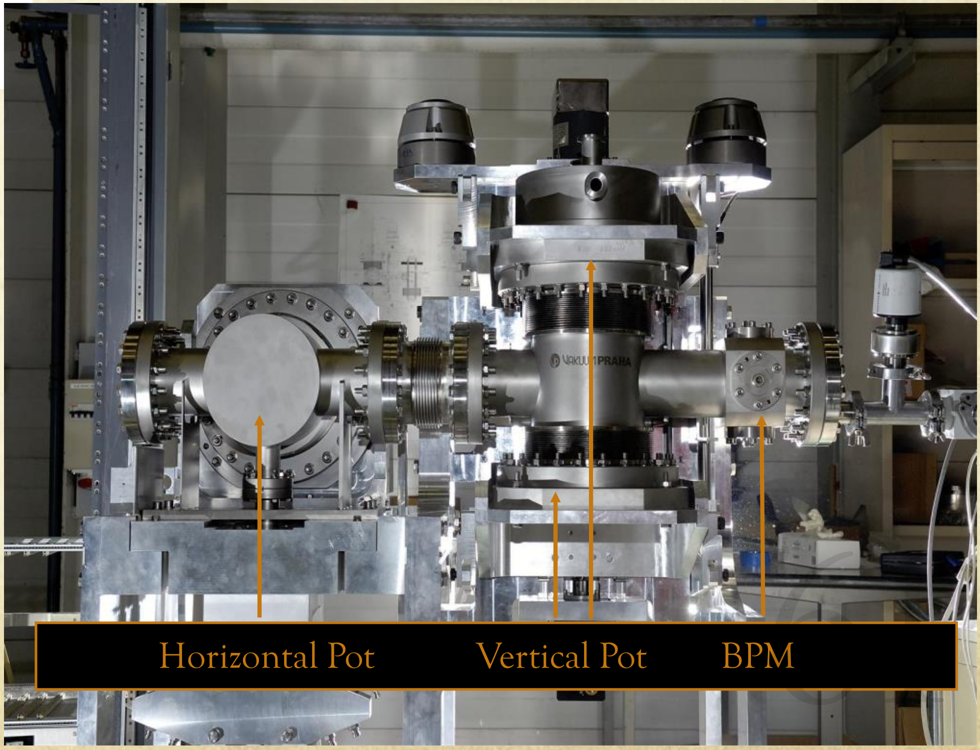
⇒ **'edgeless' detectors to minimize d**

RP station:
- 2 units at 4m distance
- 2 vertical + 1 horizontal insertions ('pots')

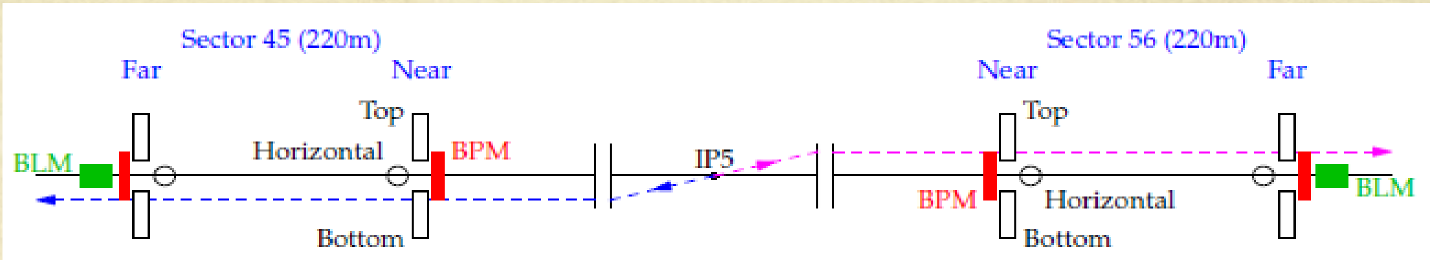


Horizontal Pot: extend acceptance; overlap for relative alignment using common track.

Absolute (w.r.t. beam) alignment from beam position monitor **(BPM)**



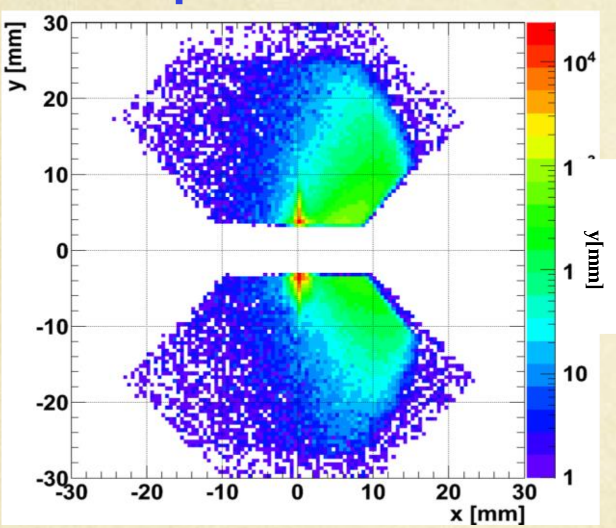
ELASTIC pp SCATTERING

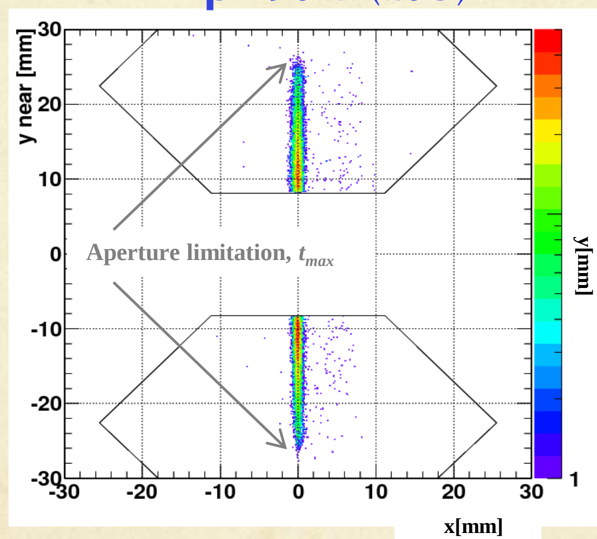


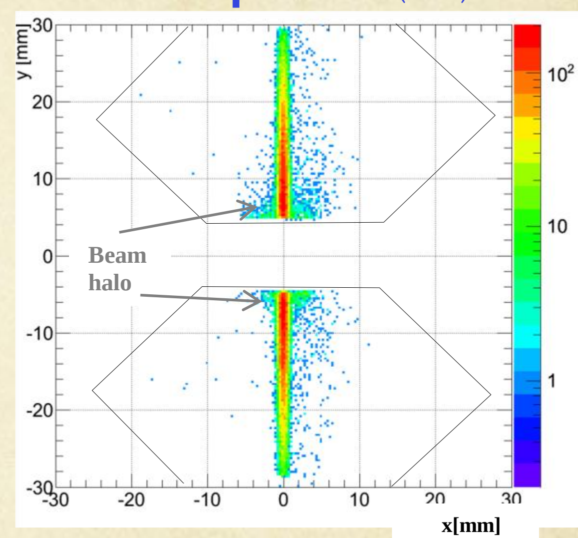
β^*=3.5m (7σ) | β^*=90m (10σ) | β^*=90m (5σ)

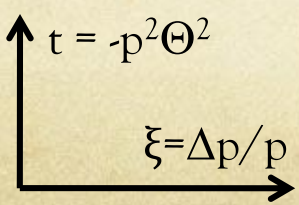
Sector 56

Sector 45



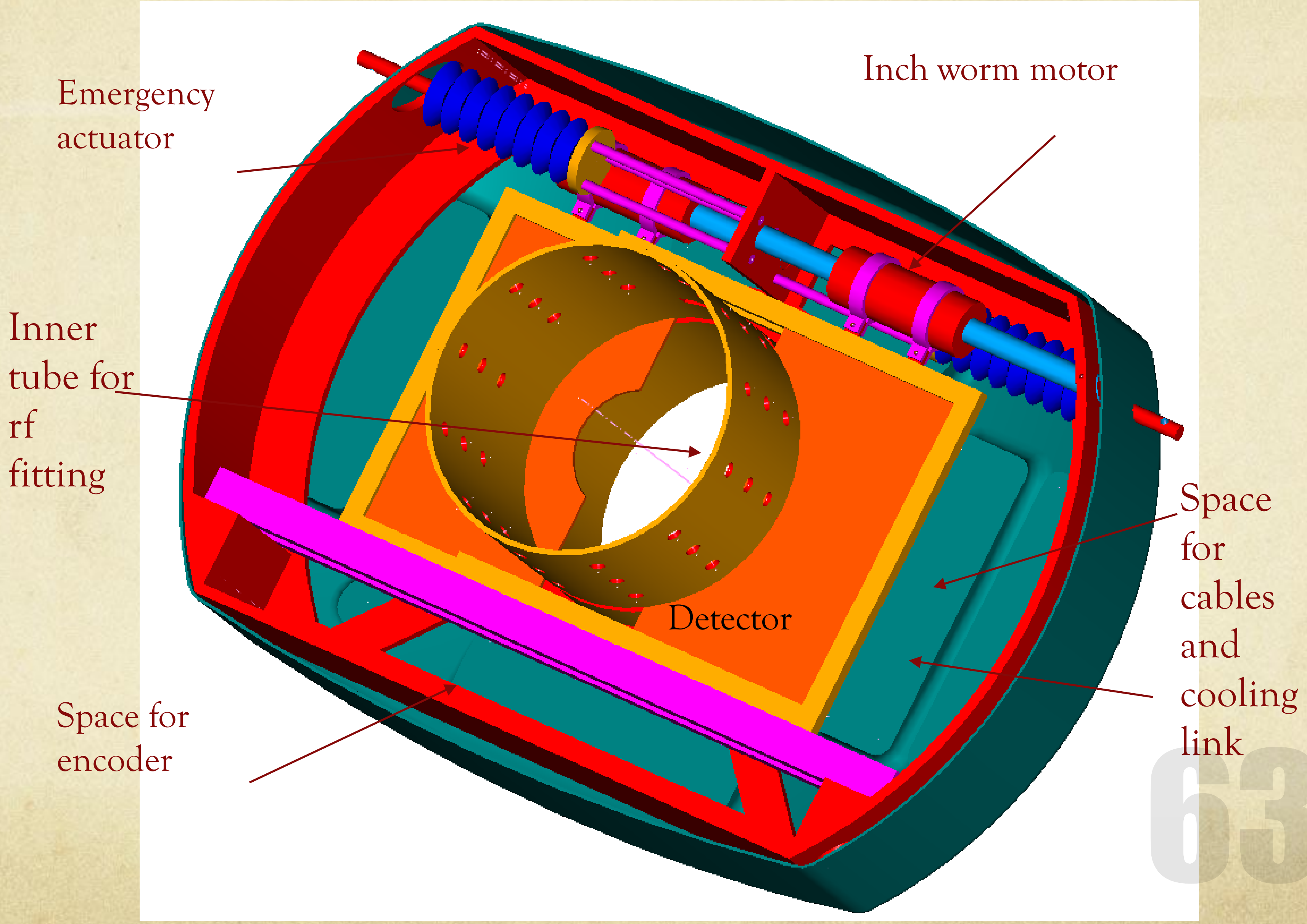




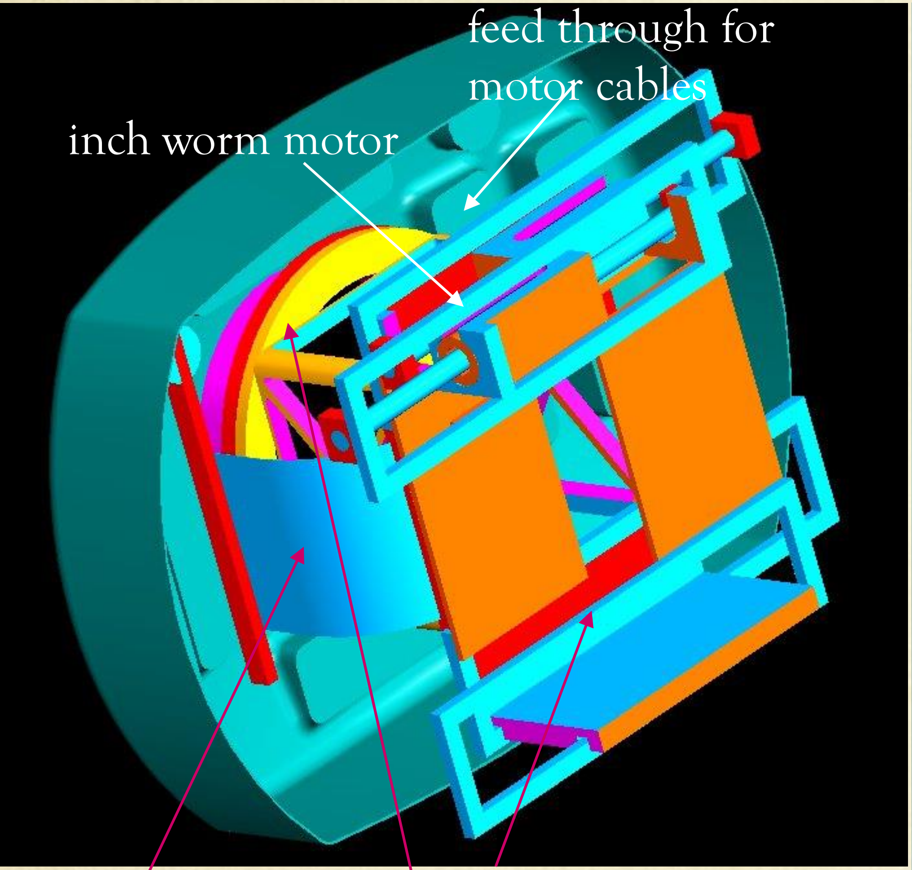


Two diagonals analysed independently

μStation - the ultimate "roman pots"



Microstation technical model 2.0

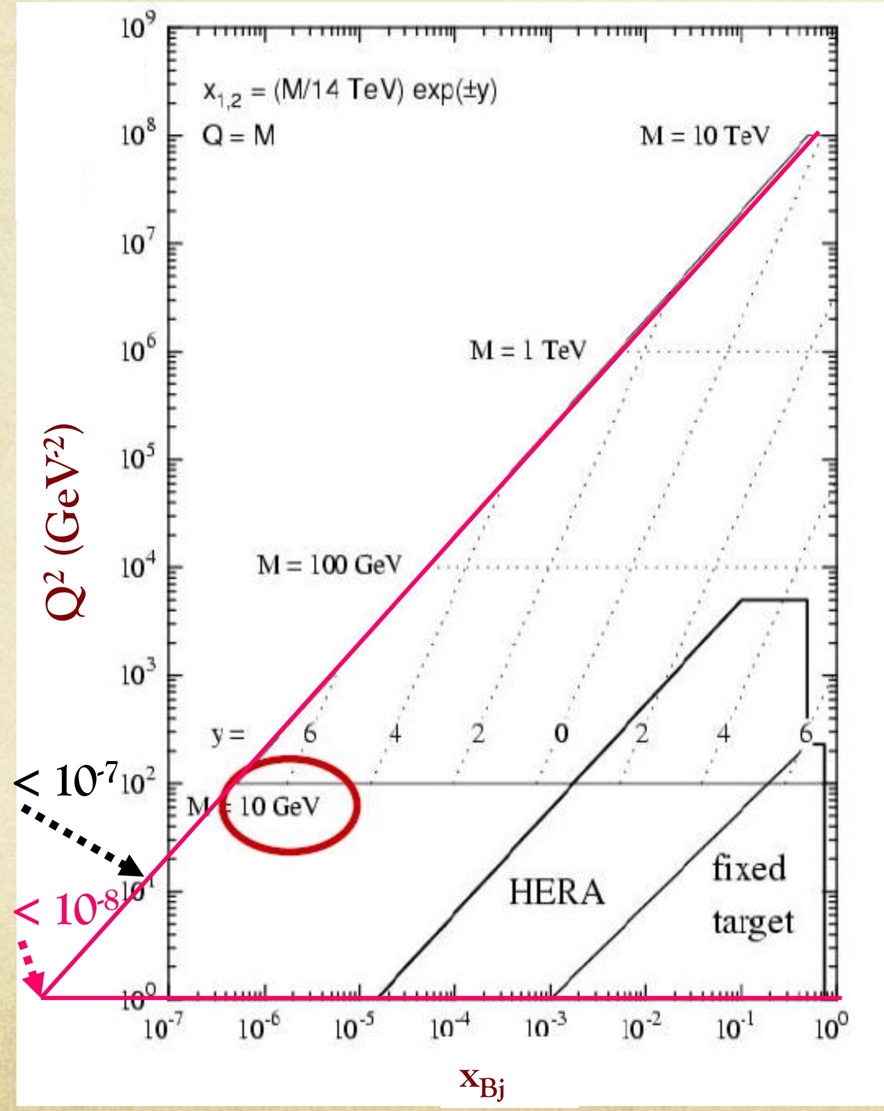


flex thermal link

space for encoders

support is welded to the main tube separately

ACCEPTANCE in x_{Bj}-Q^2



With the current forward detectors ALICE reaches forward masses of ≈ 3 GeV

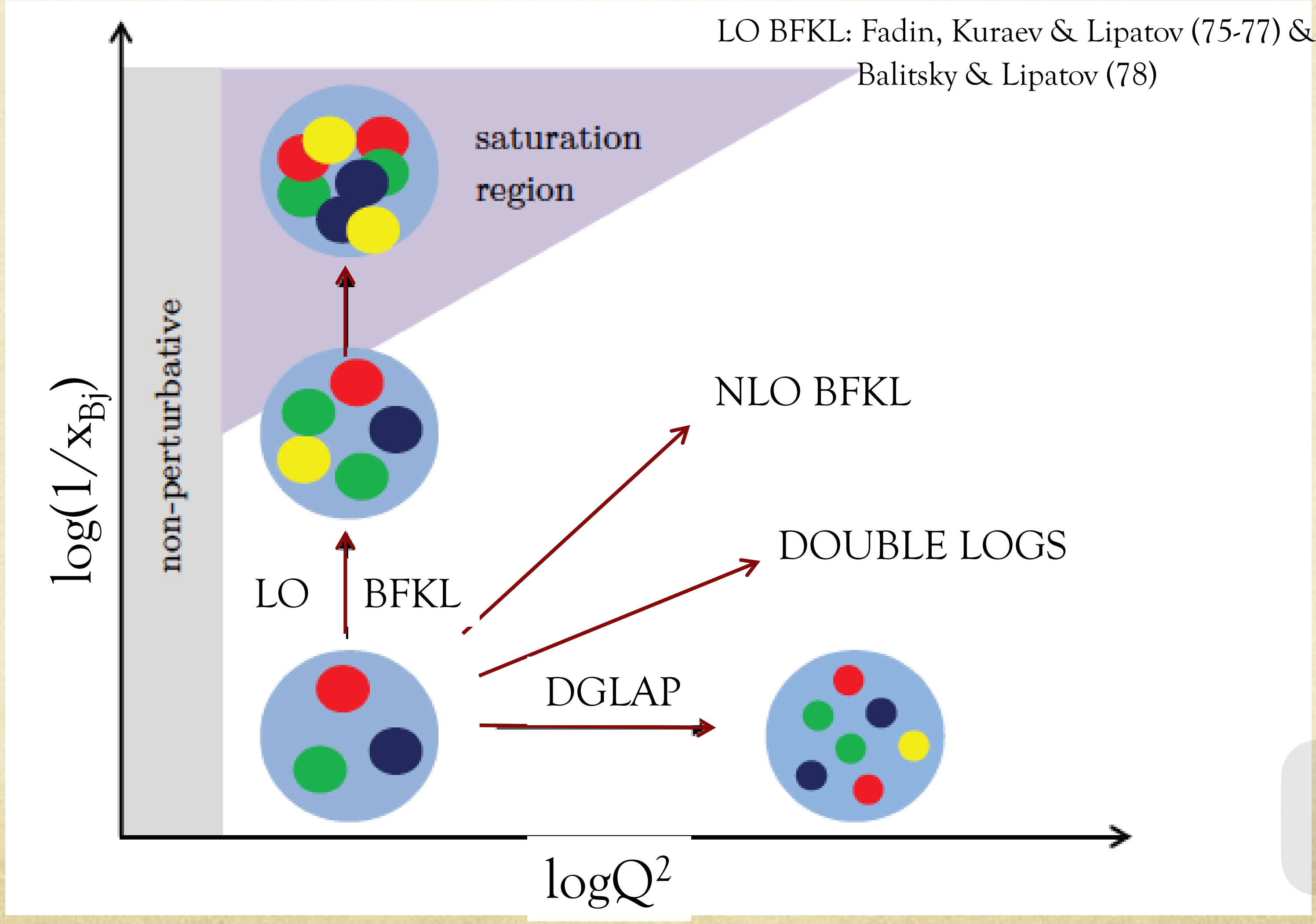
⇒ $x \leq 10^{-7}$

With a reduced efficiency reach ≈ 1.1 GeV forward masses

⇒ $x \leq 10^{-8}$

CMS and LHCb experiments are been upgrading their forward detector systems.

DIFFERENT PARTON CONFIGURATIONS ARE RESOLVED DEPENDING ON x_{Bj} and Q^2



DIFFRACTIVE SCATTERING MAPS OUT CONFIGURATIONS OF PARTONS (QUARKS AND GLUONS) CONFINED WITHIN HADRONS

- DIFFRACTION IS CHARACTERIZED BY PHERIPHERAL VACUUM FLUCTUATIONS – NUMBER FLUCTUATIONS OF 'WEE' PARTONS DOMINATE WITH INCREASING ENERGIES

- CENTRAL EXCLUSIVE PROCESS AS A GLUON FACTORY, J^{PC} QUANTUM NUMBER FILTER, **DISCOVERY MACHINE**..

- CLASSIFICATION OF DIFFRACTIVE SCATTERING ENTERS NEW ERA

- **MASSIVE DATA SETS BEING ANALYZED AT 13 TeV LHC – STAY TUNED!**


Inkilä (Tmi)Photography