# Multiple Particles Interactions in Herwig

Andrzej Siódmok

ISAPP School 2018 - LHC meets Cosmic Rays, CERN, 29th October 2018

NCN, Poland Grant No. 2016/23/D/ST2/02605

# Outline

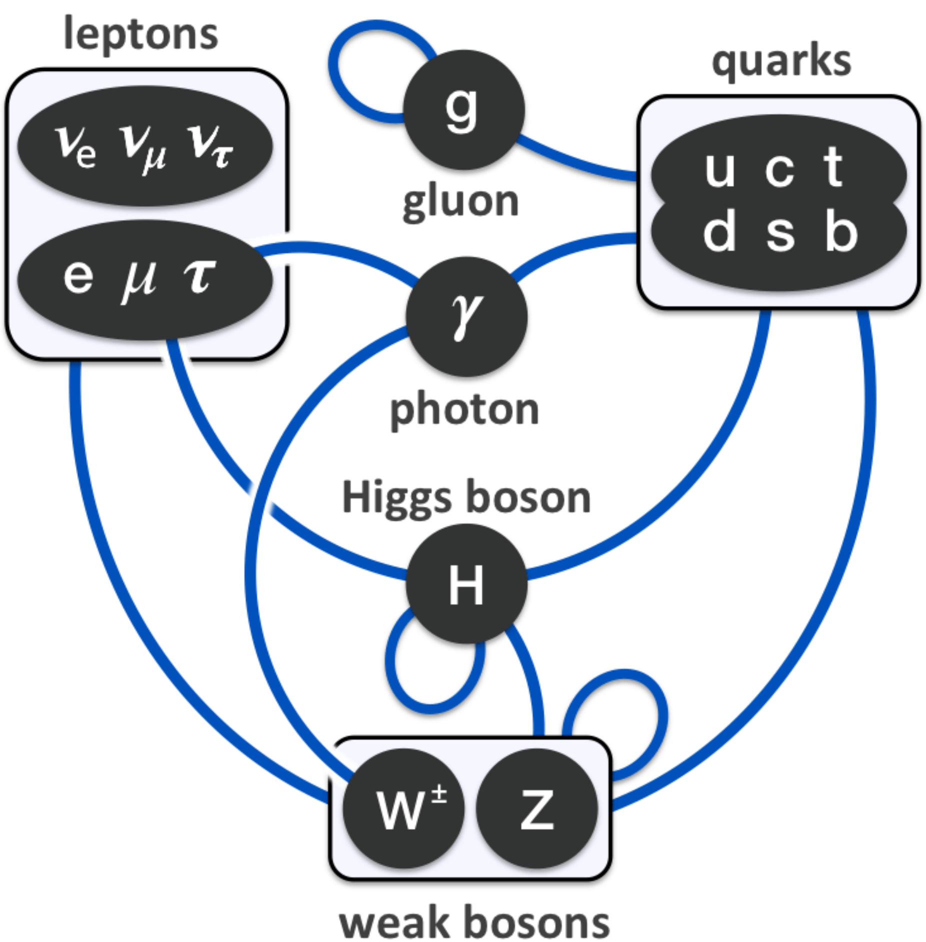
1. Motivation

2. Basic building blocks of Monte Carlo Event Generators

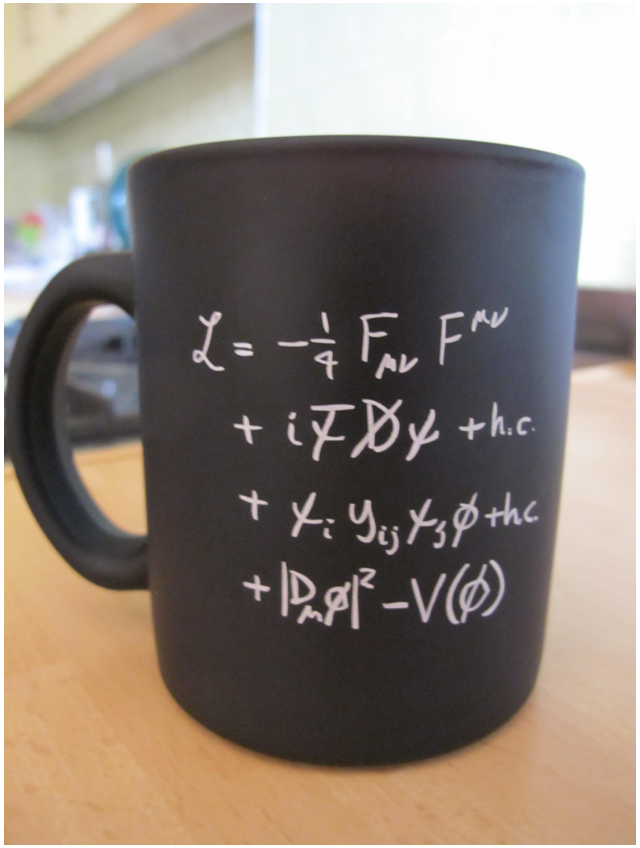
3. Multiple Particles Interactions in Herwig

4. Summary and outlook

# Standard Model
## (Forces Mediated by Gauge Bosons)



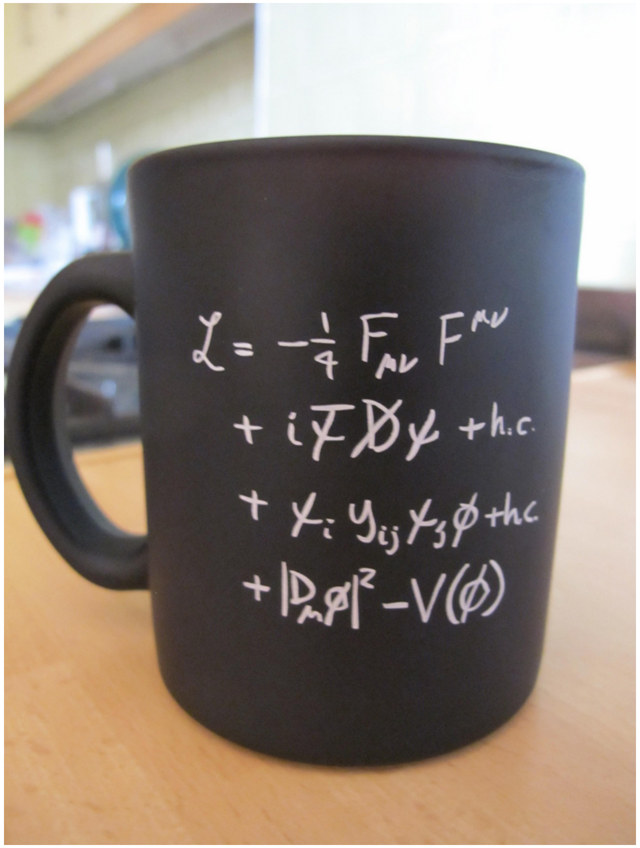

Standard Model Lagrangian



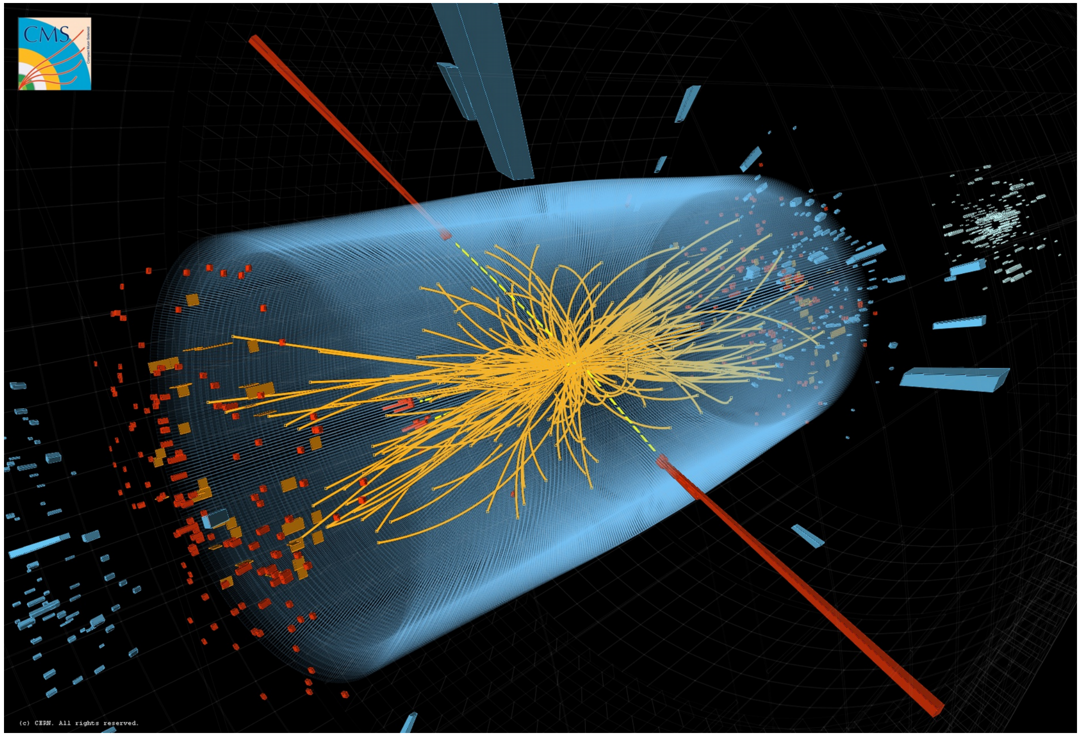
## Standard Model Interactions

There is a huge gap between a one-line formula of a fundamental theory, like the Lagrangian of the SM, and the experimental reality that it implies.

### Standard Model Lagrangian




### Experimental reality



# What Virtual Colliders are and why the are useful?

**Theory**

Lagrangian
Gauge invariance
QCD
Partons
NLO
Resummation
...

DATA MAKES YOU SMARTER

**It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.**

*Richard P. Feynman*

Fred Olness 6 September 2013 DESY

Detector simulation
Pions, Kaons, ...
Reconstruction
B-tagging efficiency
Boosted decision tree
Neural network
...

**Experiment**

# What Virtual Colliders are and why the are useful?

Theory

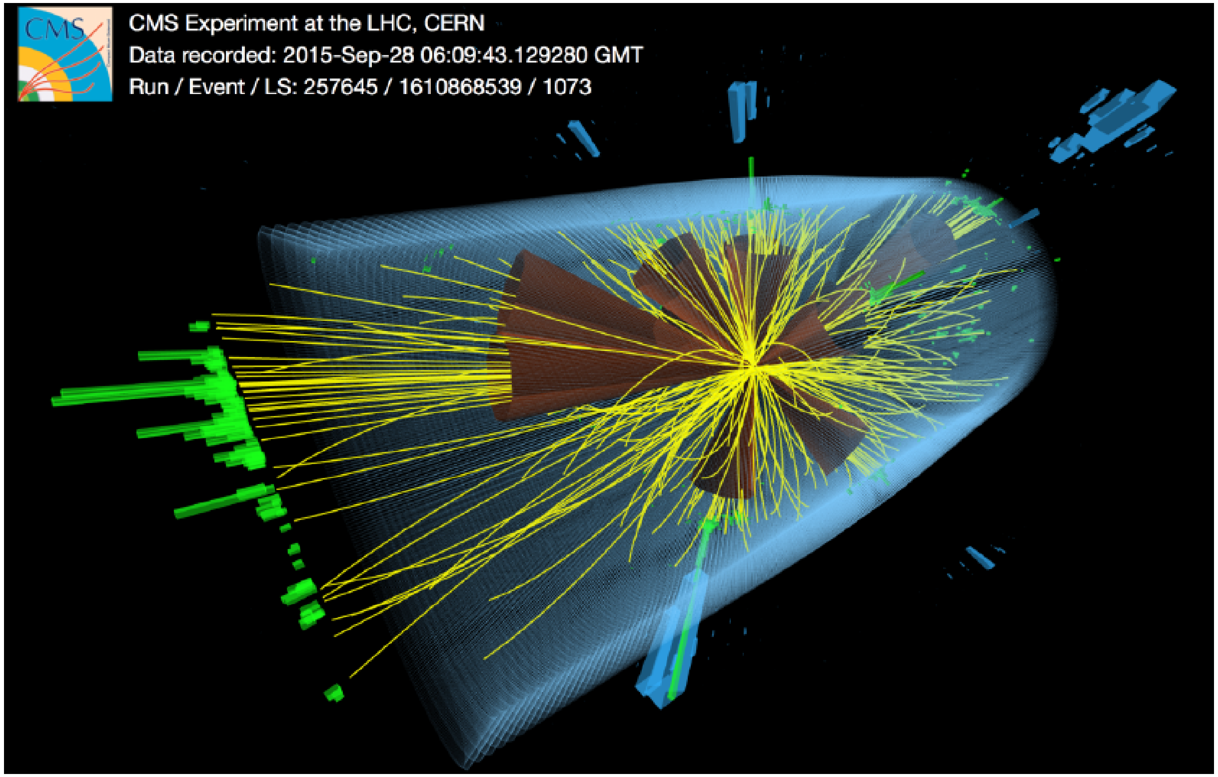
Lagrangian
Gauge invariance
QCD
Partons
NLO
Resummation
...


Detector simulation
Pions, Kaons, ...
Reconstruction
B-tagging efficiency
Boosted decision tree
Neural network
...

Experiment

# What Virtual Colliders are and why the are useful?

- General Purpose Monte Carlo (GPMC) event generators are designed to bridge that gap.




- One can think of a GPMC as a "Virtual Collider" $\Rightarrow$ Direct comparison with the data.
- Almost all HEP measurements and discoveries in the modern era have relied on GPMC generators, most notably the discovery of the Higgs boson.

# Hadron colliders and the importance of strong interactions

Relative strength of the forces at $10^{-15}$m ( = proton radius):

Strong : Electromagnetic : Weak
1 : 1 / 100 : 1/10000

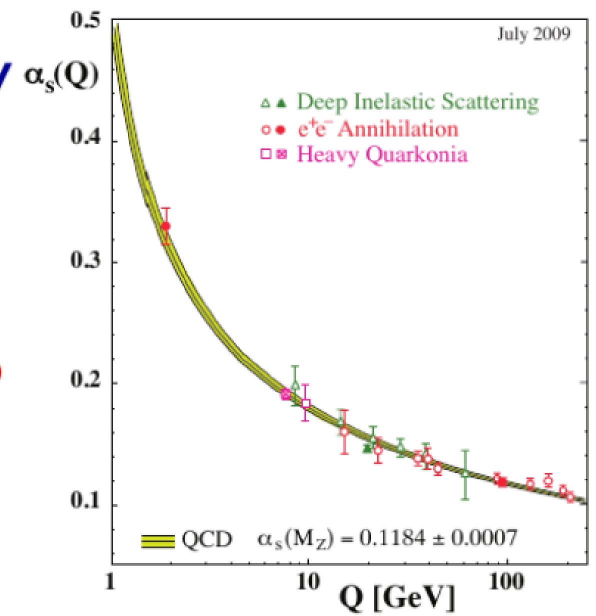
## QCD: Quantum field theory of strong interactions

(C.N. Yang, R. Mills; H. Fritzsch, M. Gell-Mann, H. Leutwyler)

- interaction carried by gluons acting on quarks and gluons
- QCD-charge: colour : of three types (`colours`: red, blue, green)

## QCD coupling strength $\alpha_s$ depends on energy

- low energy ( = long distance or time)
  - → $\alpha_s$ is large (confinement): non-perturbative regime of QCD
- high energy ( = short distance or time)
  - → $\alpha_s$ is small (asymptotic freedom): perturbative regime of QCD




Particle Data Group

[see Ralph Engel lecture]

# Complex structure of Quantum Chromodynamics – three faces of QCD

Perturbative: $\alpha_s \ll 1$

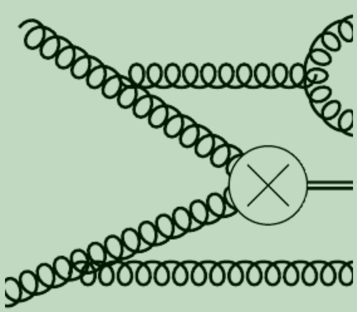
$$\sigma = \sigma_0 + \alpha_s\sigma_1 + \alpha_s^2\sigma_2 + \alpha_s^3\sigma_3 \ldots$$

$$\sigma_0 > \alpha_s\sigma_1 > \alpha_s^2\sigma_2 > \alpha_s^3\sigma_3 \ldots$$

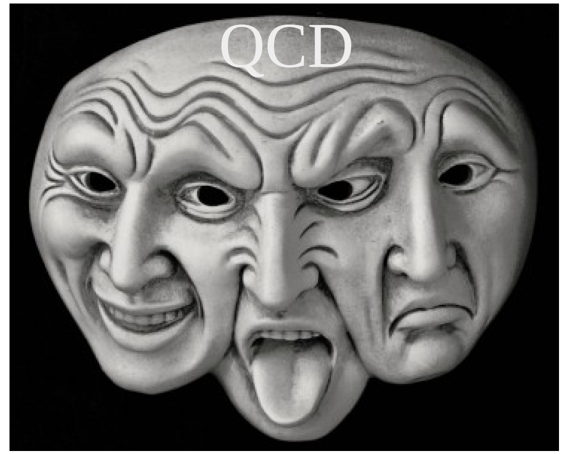
LO NLO NNLO N3LO

State of the art:

*"Higgs boson gluon-fusion production in N3LO QCD"* *Phys. Rev. Lett. 114, 212001 (2015)*



Example of one of hundreds of diagram



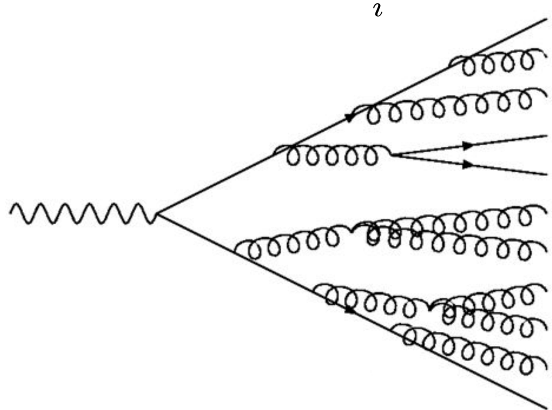

Perturbative resummation:

- enhanced terms

$$\sigma_i \supset L^i$$

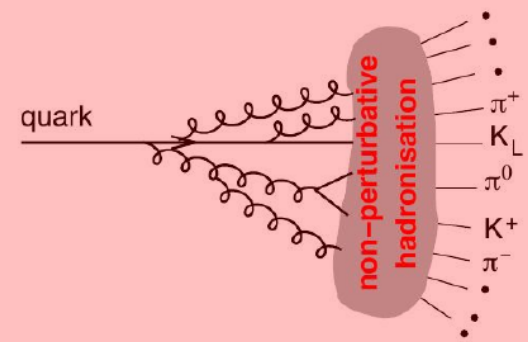
$$\sigma_0 \sim \alpha_s L \sim \alpha_s^2 L^2 \sim \alpha_s^3 L^3 \ldots$$

- Resum them $\sum_i^\infty \alpha_s^i L^i$



Non-Perturbative: $\alpha_s \gg 1$

- Perturbative techniques break down
- Non-pertubative models inspired by physical motivations
- Lattice QCD?



# What do MC event generators do?

- An “event“ is a list of particles (pions, protons, ...) with their momenta.
- The MCs generate events.
- The probability to generate an event is proportional to the (approximate!) cross section for such an event.
- Calculate Everything $\sim$ solve QCD (1M \$ prize) $\rightarrow$ requires compromise!
- Improve lowest-order perturbation theory, by including the ”most significant“ corrections $\rightarrow$ complete events (can evaluate any observable you want)

## The Workhorses: What are the Differences?

*All offer convenient frameworks for LHC physics studies, but with slightly different emphasis*:

**PYTHIA:** Successor to JETSET (begun in 1978). Originated in hadronization studies: Lund String.

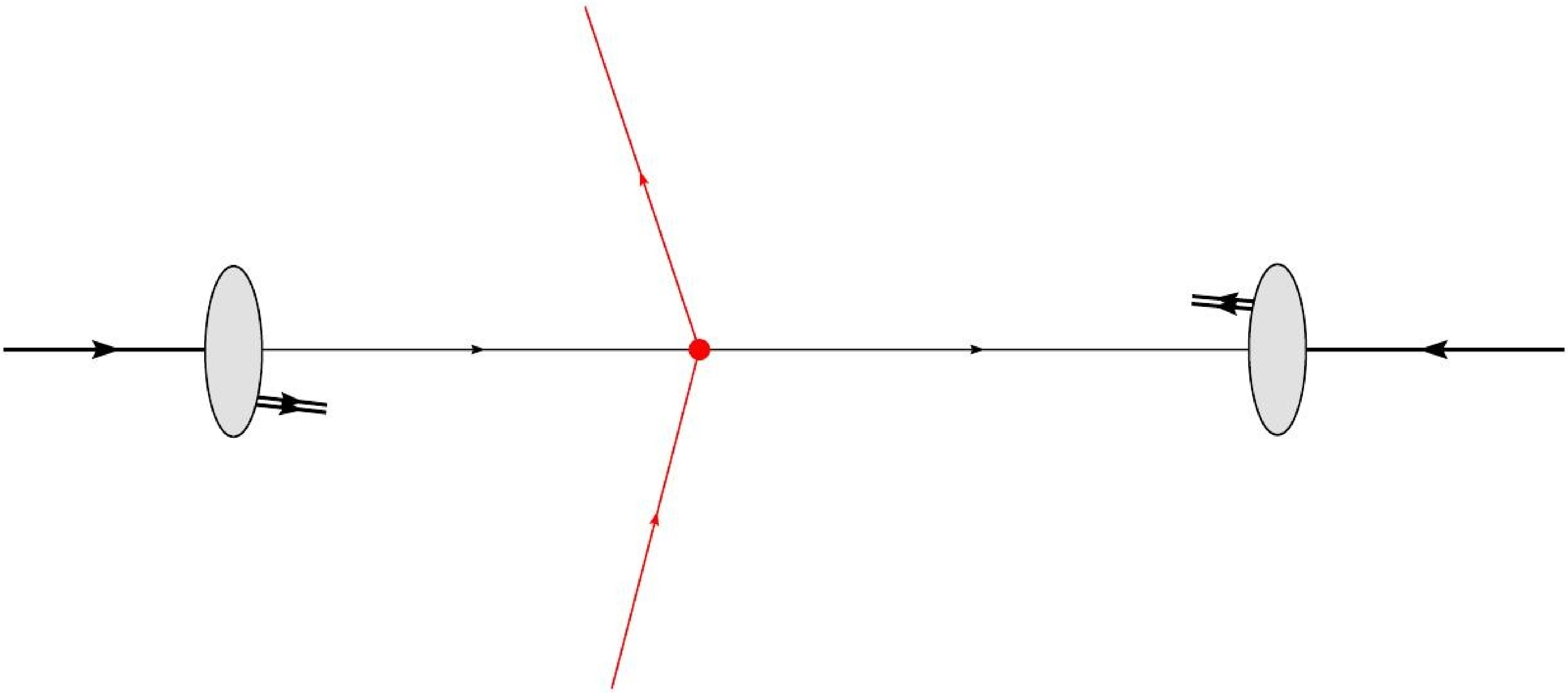
**HERWIG:** Successor to EARWIG (begun in 1984). Originated in coherence studies: angular ordering parton shower. Cluster model.

**SHERPA:** Begun in 2000. Originated in ”matching” of matrix elements to showers: CKKW.

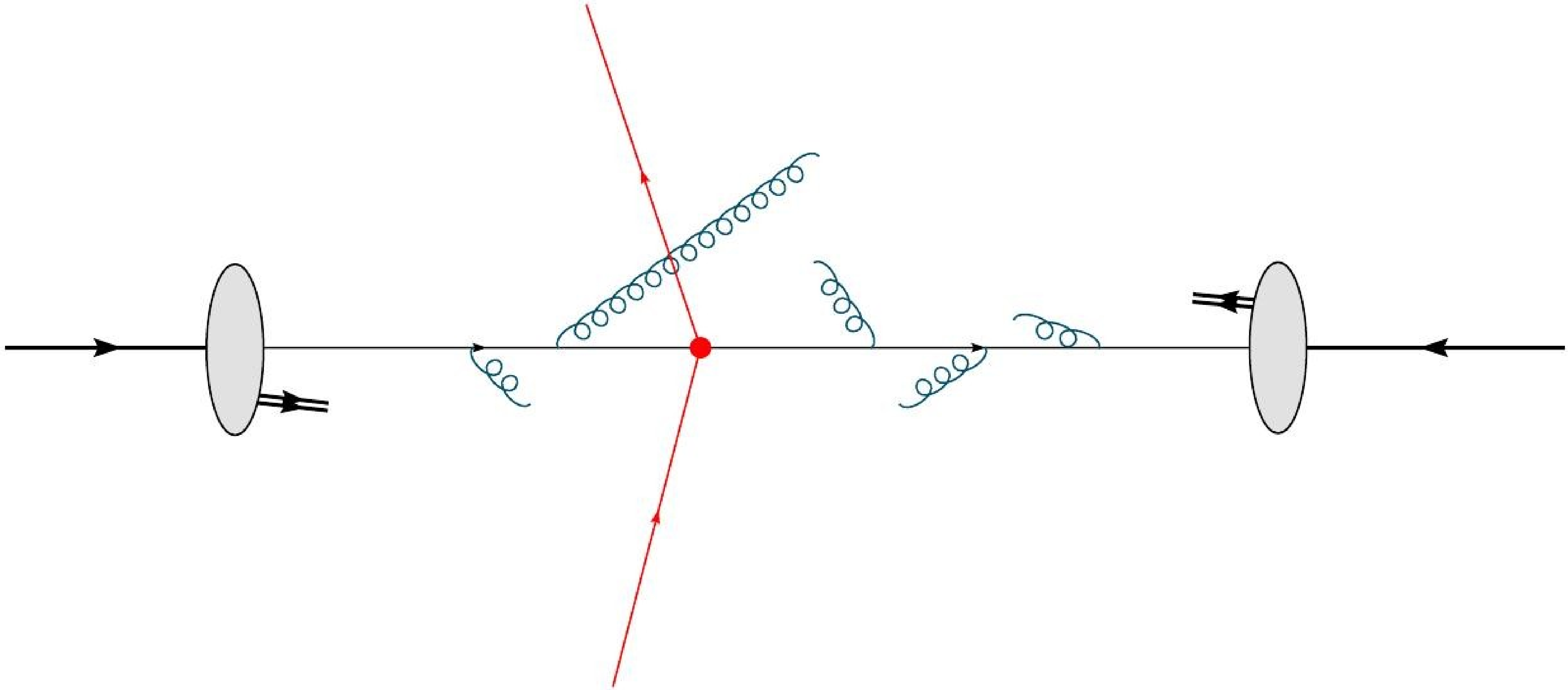
## Parton Distribution Function

# Basic building blocks of Monte Carlo Event Generators

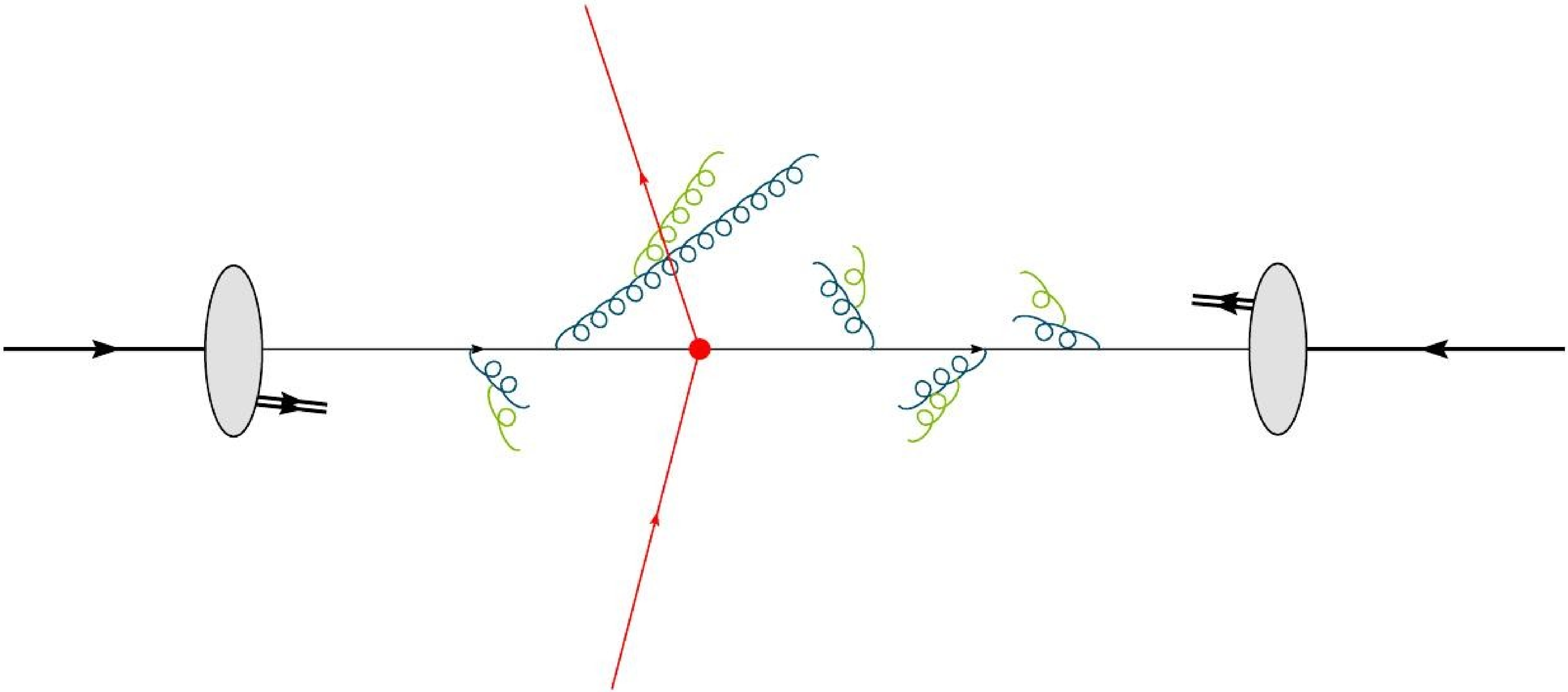
## Hard process (exact fixed-order perturbation theory)



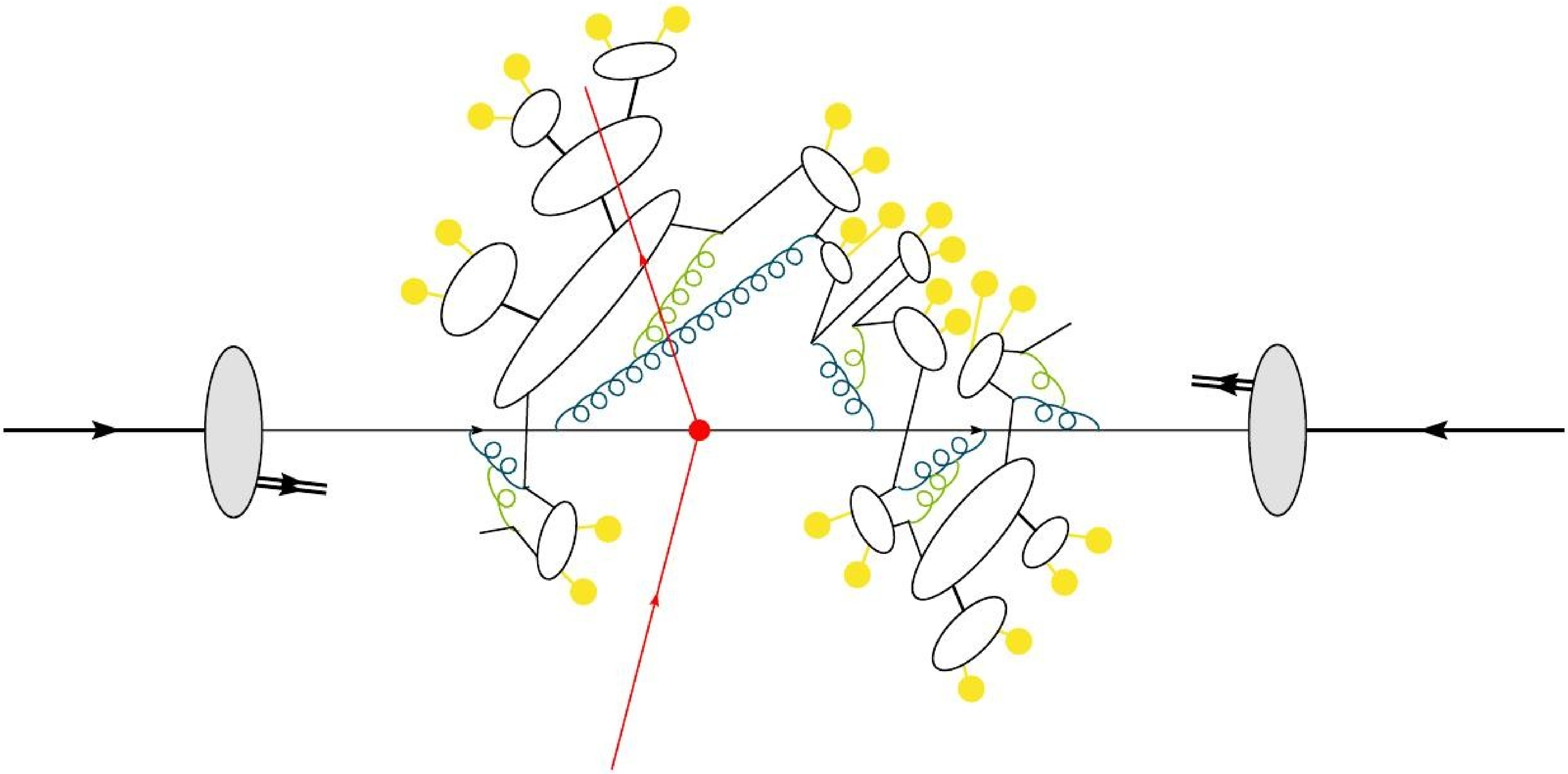
## Parton Shower (Approximate all-order perturbation theory)



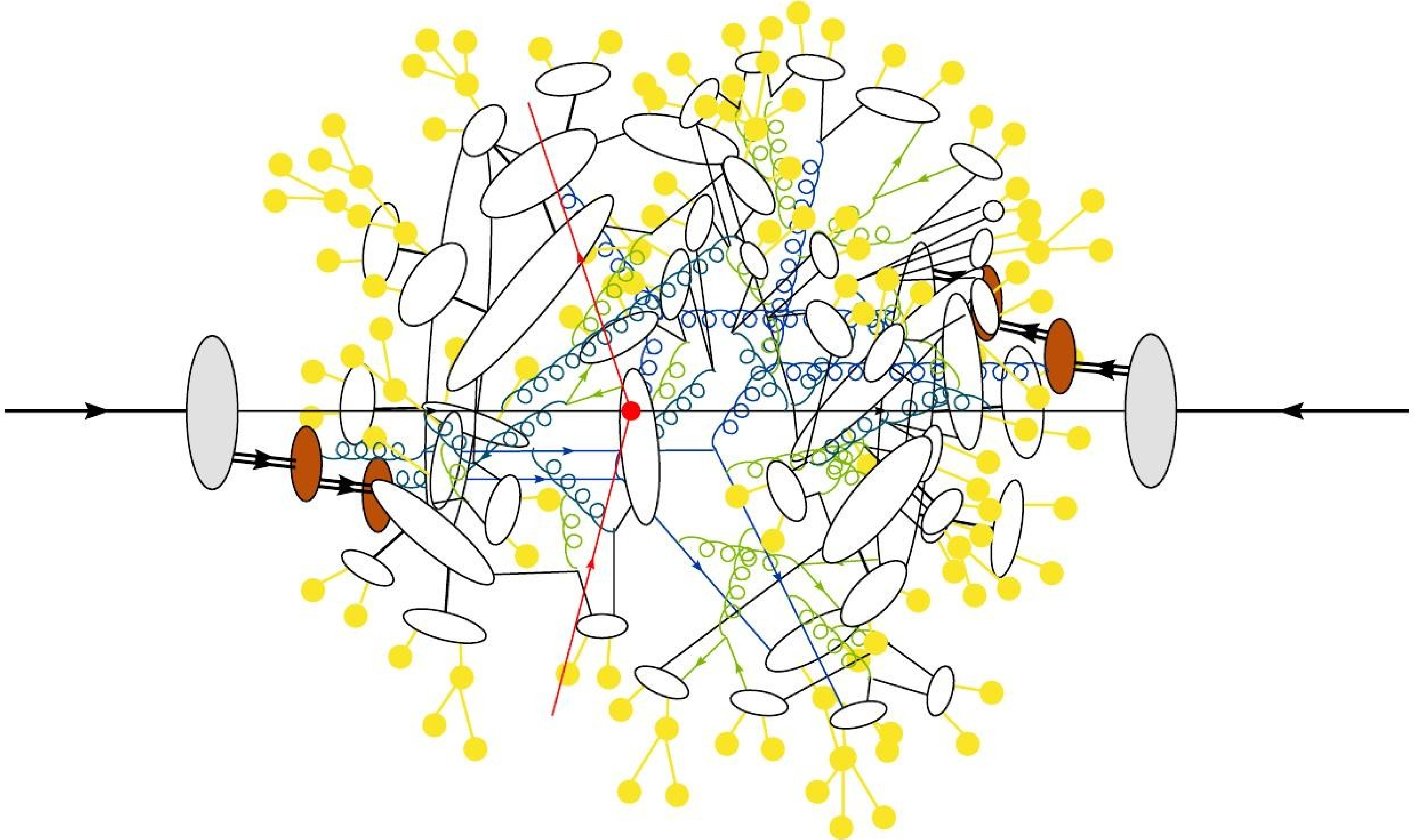
## Parton Shower (Approximate all-order perturbation theory)



Hadronization (non-perturbative semi-empirical models)



## Multiple Interactions and beam remnants



# How do we know MPI exists? Data makes you smarter!

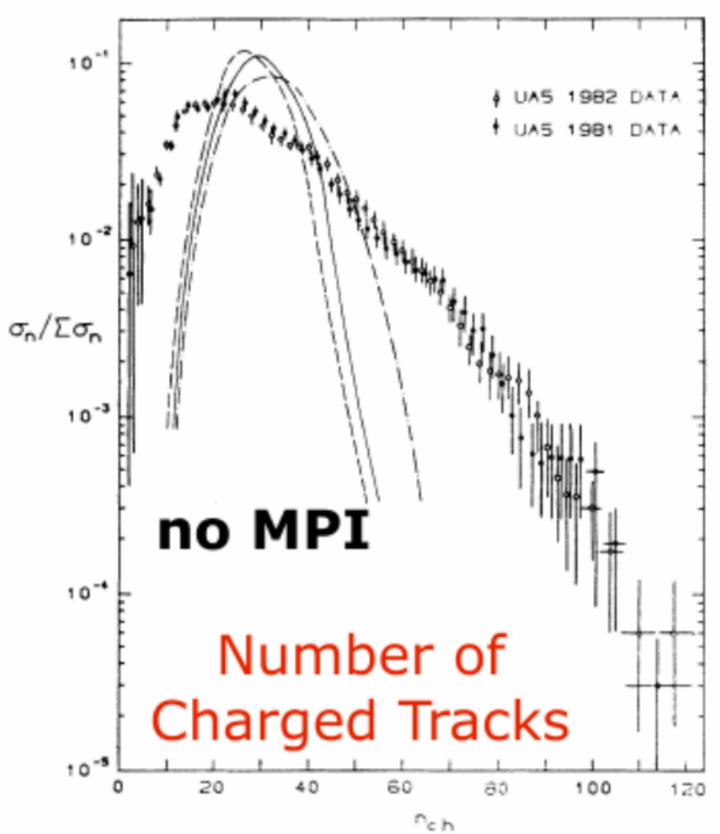



FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low $p_T$ only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

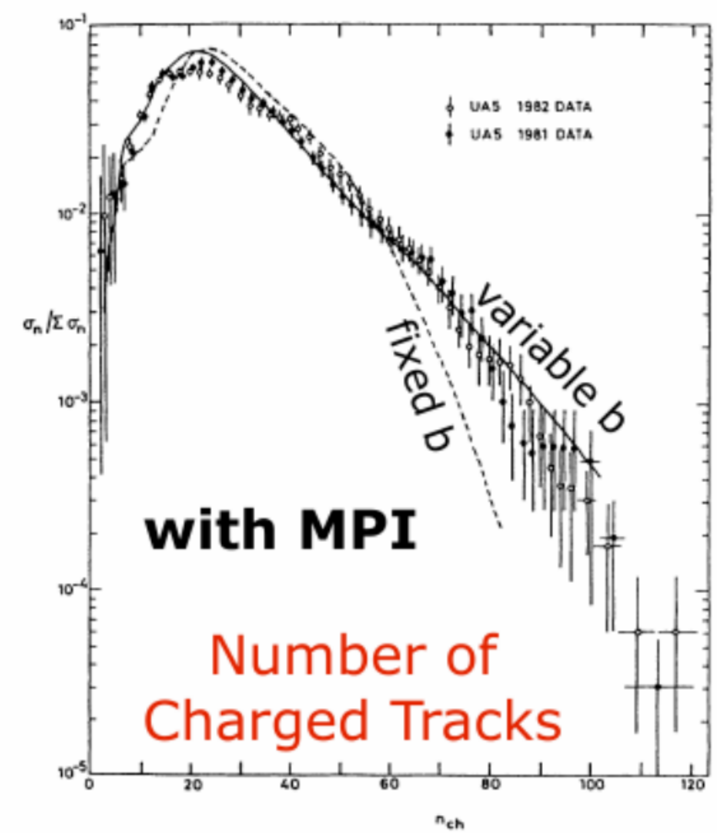



FIG. 12. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs multiple-interaction model with variable impact parameter: solid line, double-Gaussian matter distribution; dashed line, with fix impact parameter [i.e., $\bar{O}_0(b)$].

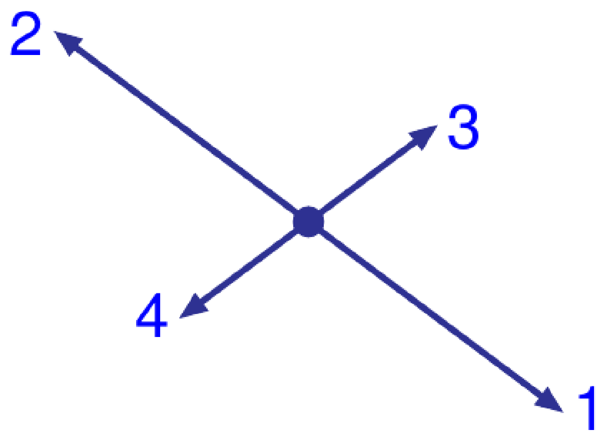
Sjöstrand & v. Zijl, Phys.Rev.D36(1987)2019

# Direct observation of multiple interactions

Five studies: AFS (1987), UA2 (1991), CDF (1993, 1997), D0 (2009)

Order 4 jets $\mathbf{p}_{\perp 1} > \mathbf{p}_{\perp 2} > \mathbf{p}_{\perp 3} > \mathbf{p}_{\perp 4}$ and define $\varphi$ as angle between $\mathbf{p}_{\perp 1} \mp \mathbf{p}_{\perp 2}$ and $\mathbf{p}_{\perp 3} \mp \mathbf{p}_{\perp 4}$ for AFS/CDF

**Double Parton Scattering**

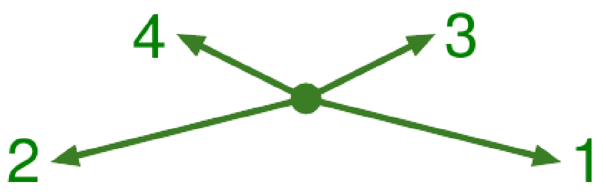



$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \approx 0$

$|\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}| \approx 0$

$\mathrm{d}\sigma/\mathrm{d}\varphi$ flat

**Double BremsStrahlung**




$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \gg 0$

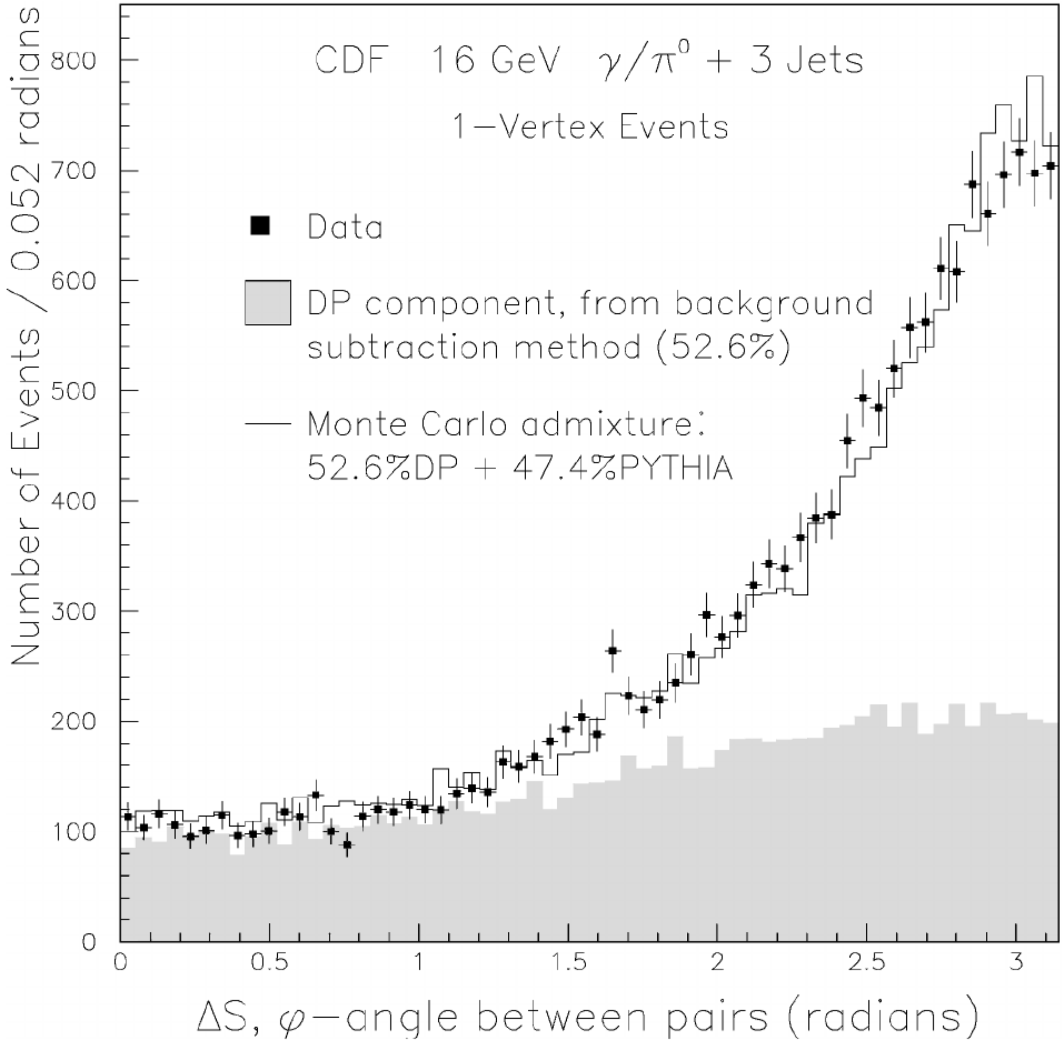
$|\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}| \gg 0$

$\mathrm{d}\sigma/\mathrm{d}\varphi$ peaked at $\varphi \approx 0/\pi$ for AFS/CDF

# Direct observation of multiple interactions

CDF: Double parton scattering in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$

[Phys. Rev. D 56, 3811-3832 (1997)]



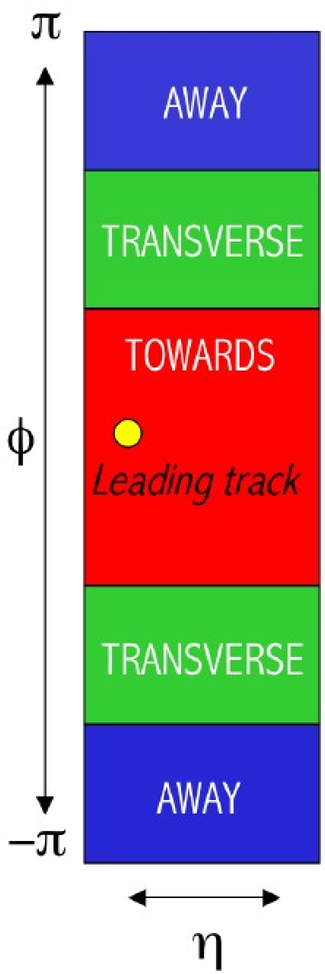
# How do we know MPI exists? Minimum Bias Measurements

- "Zero bias" - Every event in a perfect $4\pi$ detector.
- A "minimum bias" event is what one would see with a totally inclusive trigger. All events, with a minimum bias from restricted trigger conditions.
- In practice this definition depends on the experiment's trigger! Two examples:
  1. ATLAS, Minimum Bias Trigger Scintillator ($2.1 < |\eta| < 3.8$), single arm MBTS trigger fired, primary vertex reconstructed, phase spece: $p_T > 500(100)$ MeV, $|\eta| < 2.5$, $n_{ch} \geq 1 \quad (2, 6, 20)$
  2. CDF (2009), Minimum bias trigg. BBC ($3.2 < |\eta| < 5.9$), coincidence in time of signals in both forward and backward modules, primary vertex reconstructed, phase spece: $p_T > 400$ MeV, $|\eta| < 1.0$
- Typical observables:

$$\frac{1}{N_{\mathrm{ev}}} \cdot \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}, \quad \frac{1}{N_{\mathrm{ev}}} \cdot \frac{1}{2\pi p_{\mathrm{T}}} \cdot \frac{\mathrm{d}^2 N_{\mathrm{ch}}}{\mathrm{d}\eta \mathrm{d}p_{\mathrm{T}}}, \quad \frac{1}{N_{\mathrm{ev}}} \cdot \frac{\mathrm{d}N_{\mathrm{ev}}}{\mathrm{d}n_{\mathrm{ch}}} \quad \text{and} \quad \langle p_{\mathrm{T}} \rangle \text{ vs. } n_{\mathrm{ch}},$$

# How do we know MPI exists? Underlying event measurements

- Everything except the hard/interesting process




On event-by-event basis:

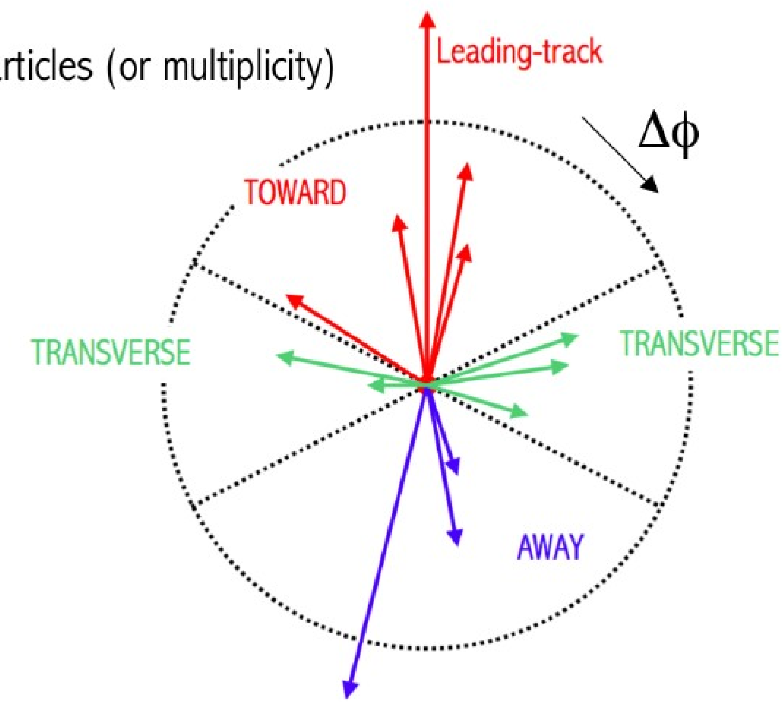
1) Identify the leading object in the event

2) Build **TRANSVERSE REGIONS** w.r.t. it

3) Compute $\Sigma p_T$ of charged particles (or multiplicity) in the different regions

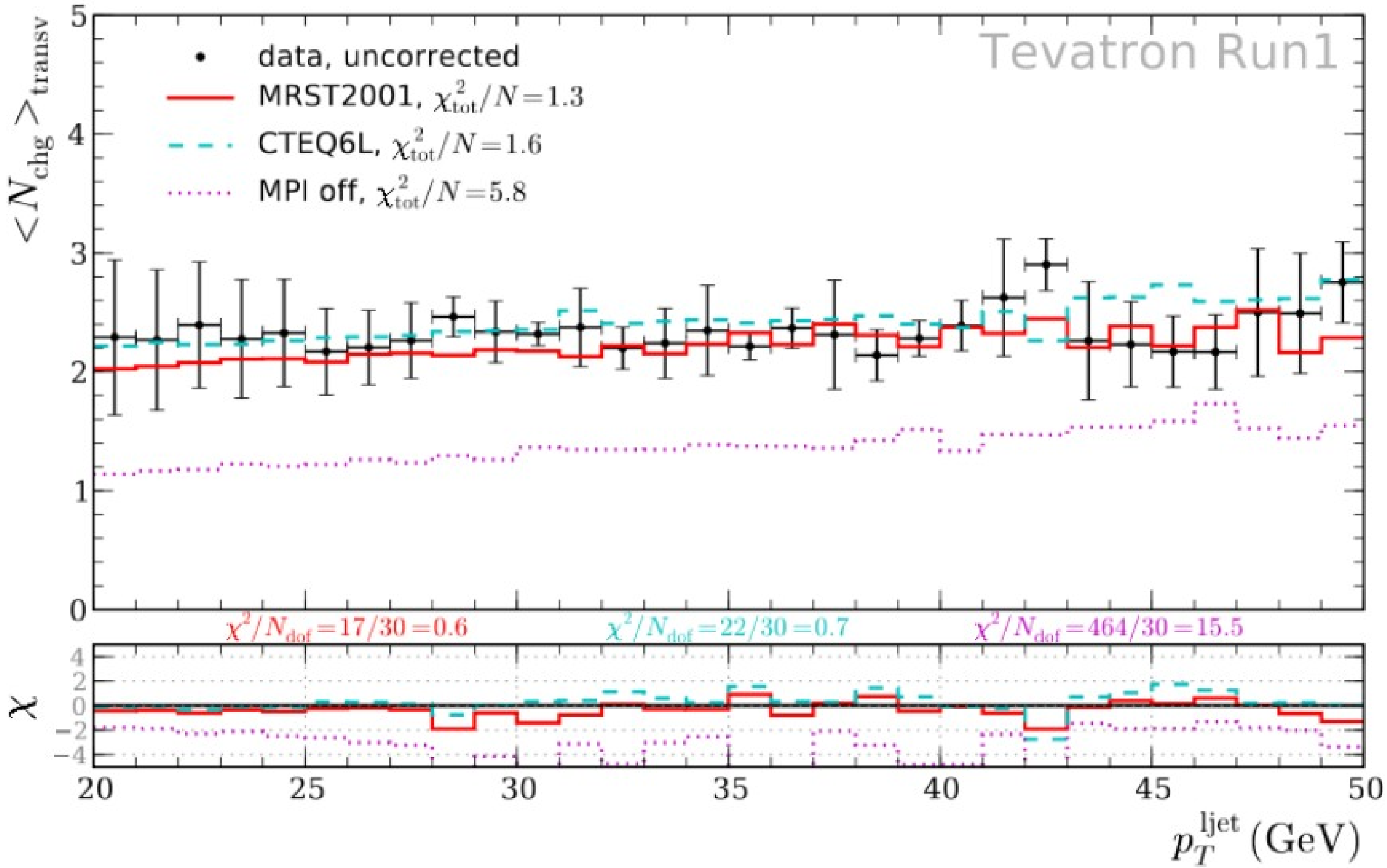
SETTINGS:

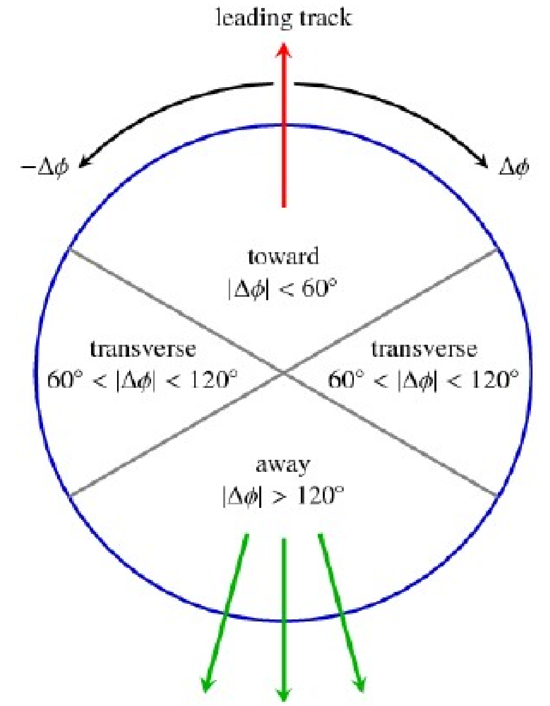
- pT > 0.5 GeV/c (tracks and leading-track)
- leading-track not included in distributions




- The transverse regions are most sensitive to the underlying event, since they are perpendicular to the axis of hardest scattering

# How do we know MPI exists? Underlying event measurements




Only $p_T^{ljet} > 20\,\text{GeV}$.

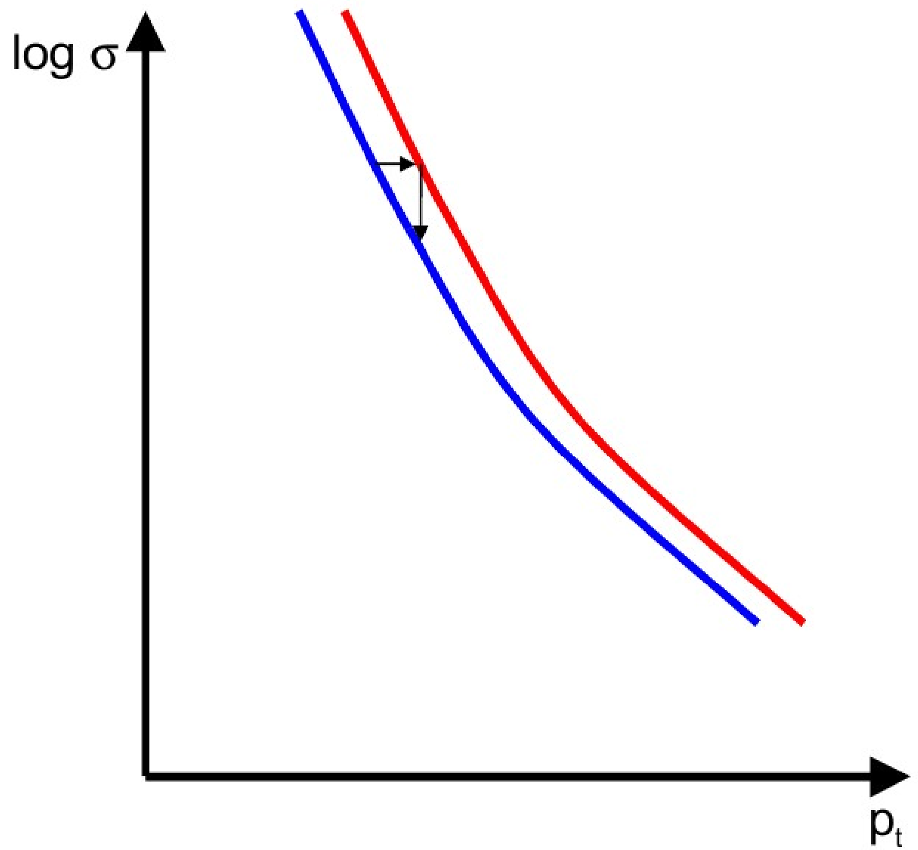
# MPI Motivation - is it really important?

Motivation:

- The minimum bias/underlying event is an unavoidable background to most collider observables and having good understand of it leads to more precise collider measurements!
- First LHC results are Minimum Bias and Underlying Event! Alice: [0911.5430], CMS [1002.0621], ATLAS [1003.3124] so it must be important ;)
- These will be particularly relevant for the LHC as, when it is operated at design luminosity, rare signal events will be embedded in a background of more than 20 near-simultaneous minimum-bias collisions.
- Any realistic experiment simulation event generator needs to be able to model these effects.
- “Don’t worry, we will measure and subtract it” But... fluctuations and correlations on an event-by-event basis are crucial.

# MPI Motivation - is it really important?

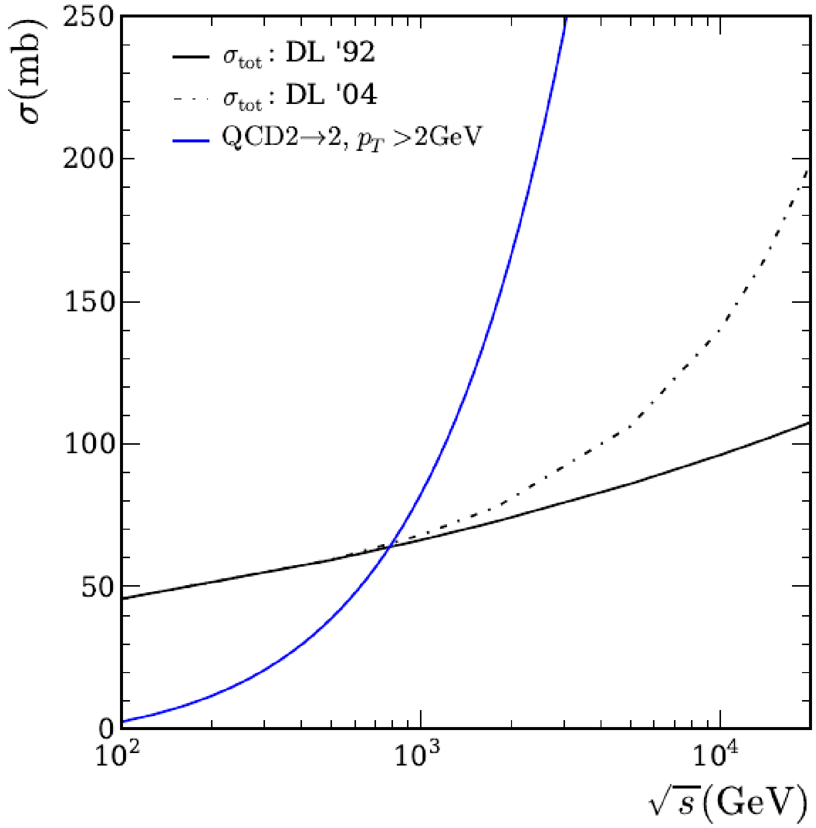
- “Don’t worry, we will measure and subtract it” But... fluctuations and correlations on an event-by-event basis are crucial.




- Steep distribution ⇒ small sideways shift = large vertical
- Rare fluctuations can have a huge influence

Inclusive hard jet cross section in pQCD:

$$\sigma^{\rm inc}(s, p_t^{\rm min}) = \sum_{i,j} \int_{p_t^{\rm min\,2}} \mathrm{d}p_t^2 \int \mathrm{d}x_1 \mathrm{d}x_2 \; f_i(x_1, Q^2)\, f_j(x_2, Q^2) \; \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$




$\sigma^{\rm inc} > \sigma_{\rm tot}$ eventually

Interpretation:

- $\sigma^{\rm inc}$ counts all partonic scatters in a single *pp* collision
- more than a single interaction

$$\sigma^{\rm inc} = \langle n_{\rm dijets} \rangle \sigma_{\rm inel}$$

# MPI Eikonal model basics

Use eikonal approximation (= independent scatters). Leads to Poisson distribution of number $m$ of additional scatters,

$$P_m(\vec{b}, s) = \frac{\bar{n}(\vec{b}, s)^m}{m!} \mathrm{e}^{-\bar{n}(\vec{b}, s)} \, .$$

Then we get $\sigma_{\text{inel}}$:

$$\sigma_{\text{inel}} = \int \mathrm{d}^2\vec{b} \sum_{n=1}^{\infty} P_m(\vec{b}, s) = \int \mathrm{d}^2\vec{b} \left(1 - \mathrm{e}^{-\bar{n}(\vec{b}, s)}\right) \, .$$

Cf. $\sigma_{\text{inel}}$ from scattering theory in eikonal approx. with scattering amplitude $a(\vec{b}, s) = \frac{1}{2i}(\mathrm{e}^{-\chi(\vec{b}, s)} - 1)$

$$\sigma_{\text{inel}} = \int \mathrm{d}^2\vec{b} \left(1 - \mathrm{e}^{-2\chi(\vec{b}, s)}\right) \qquad \Rightarrow \qquad \chi(\vec{b}, s) = \frac{1}{2}\bar{n}(\vec{b}, s) \, .$$

$\chi(\vec{b}, s)$ is called *eikonal* function.

# MPI Eikonal model basics – Overlap function

Assumptions:

- the distribution of partons in hadrons factorizes with respect to the b and x dependence ⇒ average number of parton collisions:

$$\bar{n}(\vec{b}, s) = L_{\text{partons}}(x_1, x_2, \vec{b}) \otimes \sum_{ij} \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$
$$= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$
$$\times D_{i/A}(x_1, p_t^2, |\vec{b}'|) D_{j/B}(x_2, p_t^2, |\vec{b} - \vec{b}'|)$$
$$= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$
$$\times f_{i/A}(x_1, p_t^2) G_A(|\vec{b}'|) f_{j/B}(x_2, p_t^2) G_B(|\vec{b} - \vec{b}'|)$$
$$= A(\vec{b}) \sigma^{\text{inc}}(s; p_t^{\text{min}}) \, .$$

- at fixed impact parameter b, individual scatterings are independent (leads to the Poisson distribution)

# MPI Eikonal model basics – Overlap function

From assumptions:

- at fixed impact parameter b, individual scatterings are independent,
- the distribution of partons in hadrons factorizes with respect to the b and x dependence.

we get the average number of partonic collisions at a given b value is

$$\bar{n}(b,s) = A(b)\sigma^{inc}(s;p_t^{\min}) = 2\chi(b,s)$$

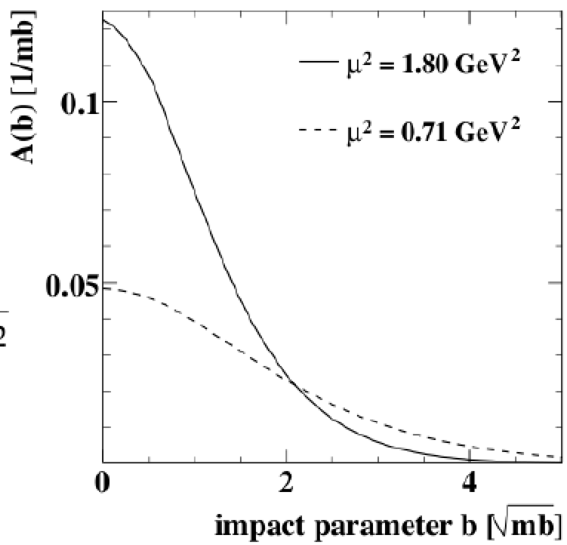
where $A(b)$ is the partonic overlap function of the colliding hadrons

$$A(b) = \int d^2\vec{b}' G_A(|\vec{b}'|) G_B(|\vec{b} - \vec{b}'|)$$

$G(\vec{b})$ from electromagnetic FF:

$$G_p(\vec{b}) = G_{\bar{p}}(\vec{b}) = \int \frac{d^2\vec{k}}{(2\pi)^2} \frac{e^{i\vec{k}\cdot\vec{b}}}{(1+\vec{k}^2/\mu^2)^2}$$

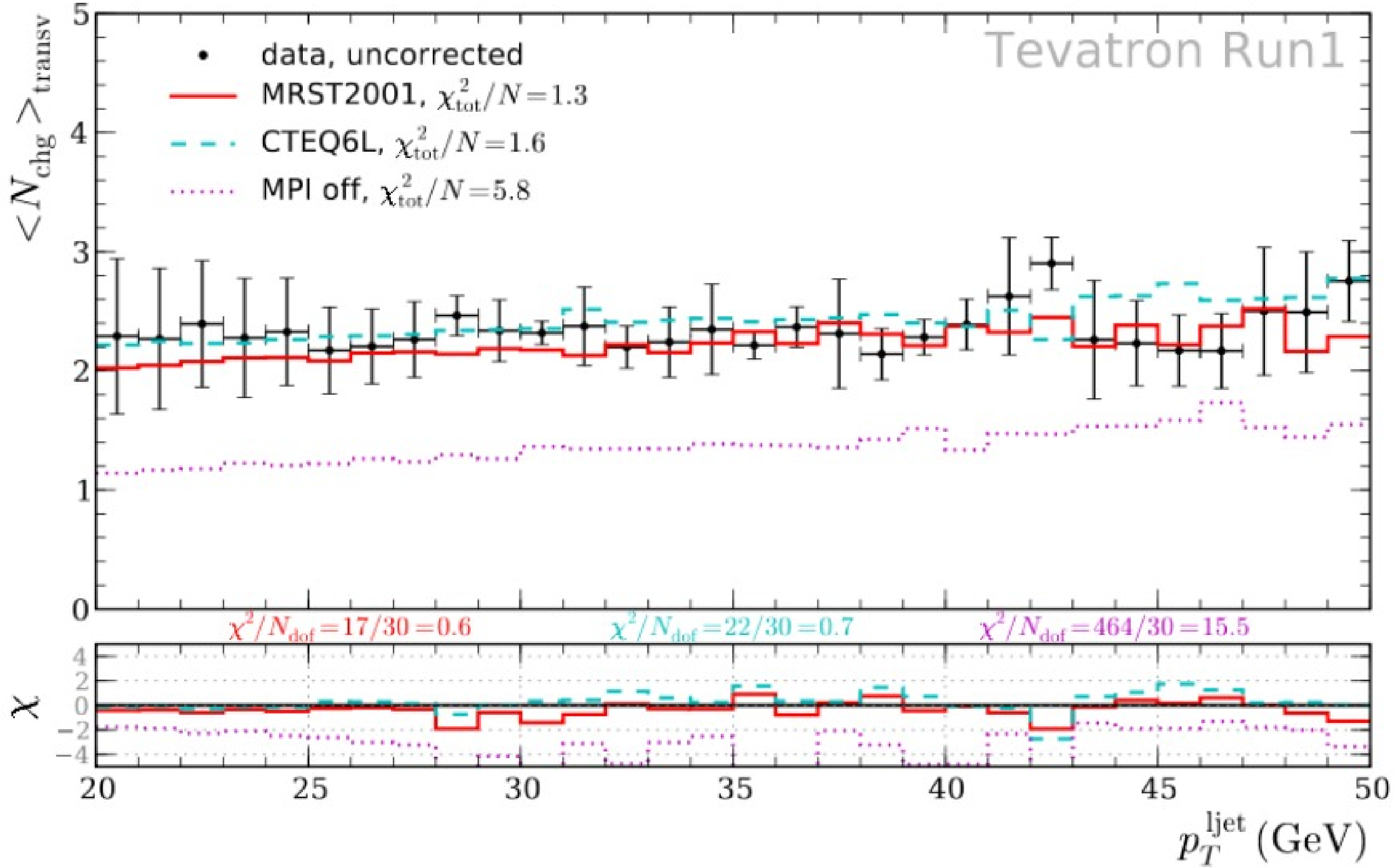
But $\mu^2$ *not fixed* to the *electromagnetic* 0.71 GeV$^2$. Free for colour charges.

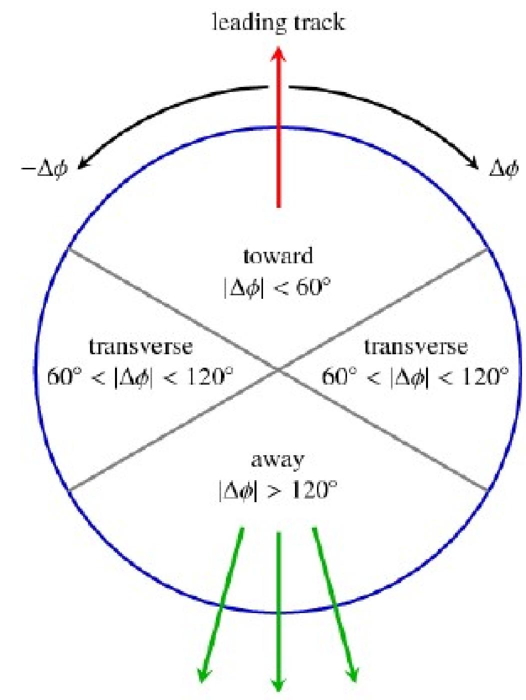



$\Rightarrow$ Two main parameters: $\mu^2, p_t^{\min}$.

# MPI Eikonal model basics – Semihard MPI and UE data

Good description of Run I Underlying event data ($\chi^2 = 1.3$).




Only $p_T^{ljet} > 20$GeV.

So far only hard MPI. Now extend to soft interactions with

$$\chi_{\text{tot}}(\vec{b}, s) = \frac{1}{2}\left(A(\vec{b};\mu)\sigma^{\text{inc}}\text{hard}(s;p_t^{\text{min}}) + A(\vec{b};\mu_{\text{soft}})\sigma^{\text{inc}}_{\text{soft}}\right)$$

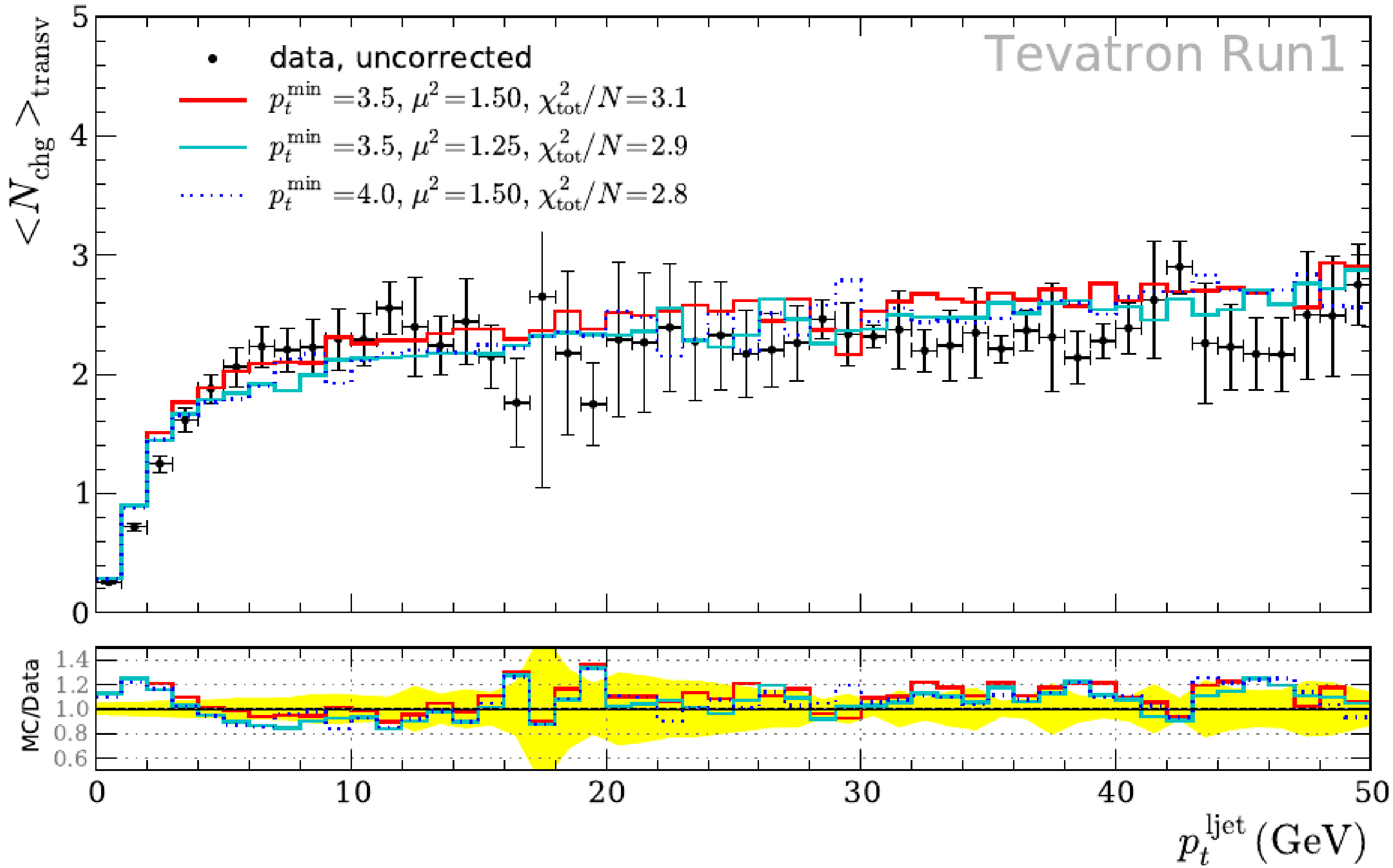
Fix the two parameters $\mu_{\text{soft}}$ and $\sigma^{\text{inc}}_{\text{soft}}$ from two constraints

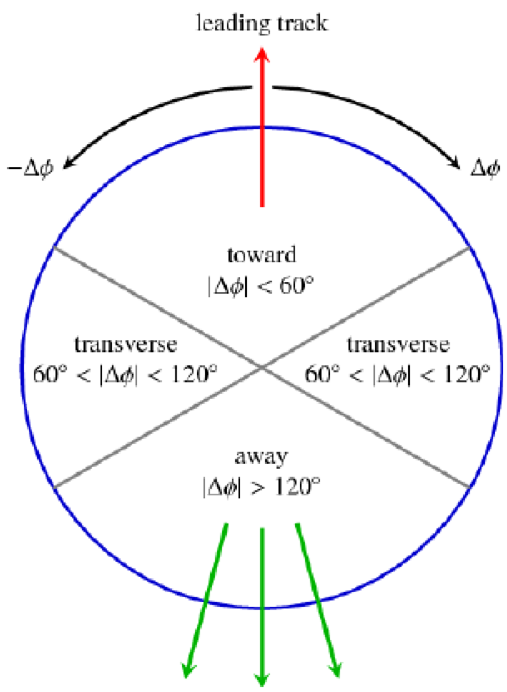
$$\sigma_{\text{tot}}(s) \stackrel{!}{=} 2\int \mathrm{d}^2\vec{b}\left(1 - \mathrm{e}^{-\chi_{\text{tot}}(\vec{b},s)}\right) ,$$

$$b_{\text{el}}(s) \stackrel{!}{=} \int \mathrm{d}^2\vec{b}\,\frac{b^2}{\sigma_{\text{tot}}}\left(1 - \mathrm{e}^{-\chi_{\text{tot}}(\vec{b},s)}\right) .$$

(measured/well predicted)

# MPI Eikonal model basics – extention to soft MPI



**What we have so far:**

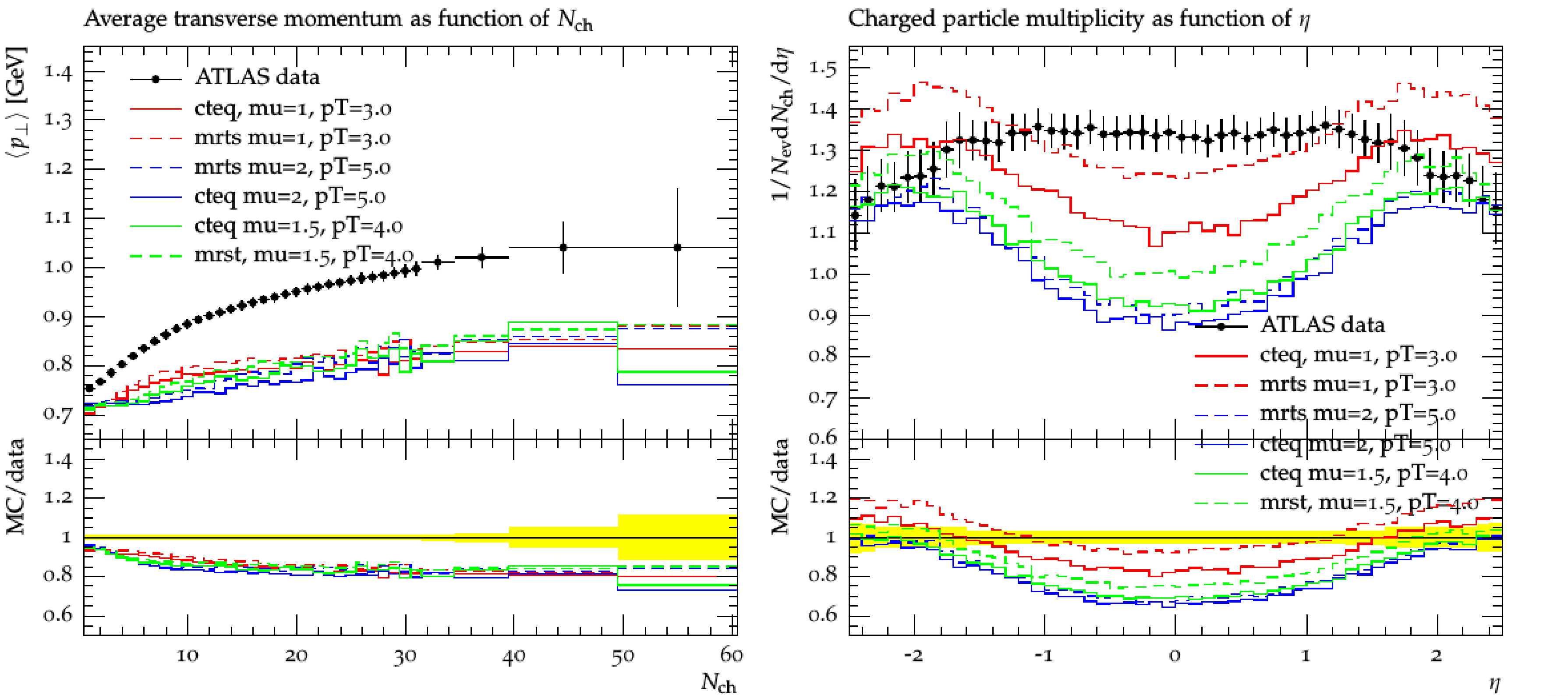
- Unitarized jet cross sections
- Fulfil constaints from $\sigma_{\text{tot}}$ and $\sigma_{\text{el}}$.
- Simple model with similar overlap functions.
- No additional (explicit) energy dependence.
- Left with freedom in parameter space.

$\Longrightarrow$ *Look at LHC results (900 GeV).*

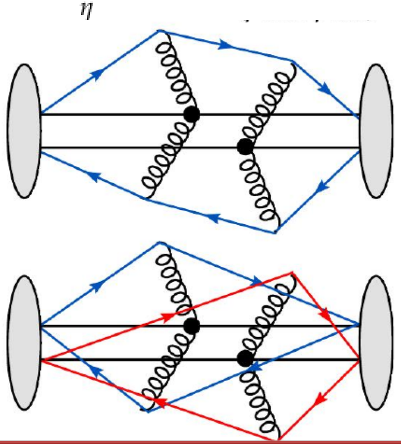
- ATLAS charged particles in Min Bias.

# On to the LHC

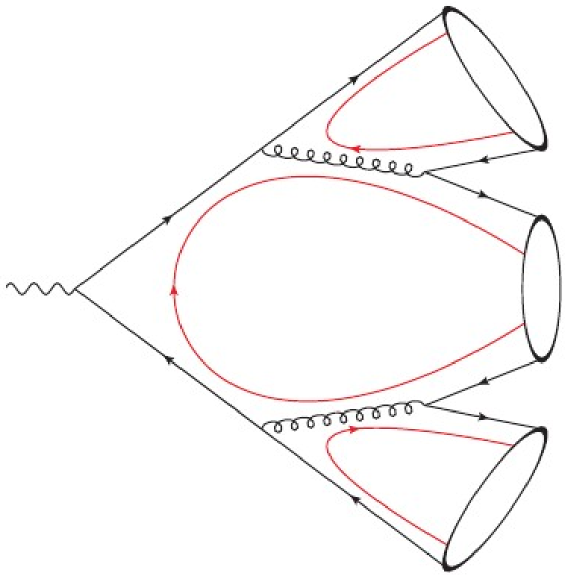
- ATLAS charged particles in Min Bias ($N_{ch} \geq 1,\ p_T > 500MeV,\ |\eta| < 2.5$)




- oops, not so nice...
- despite very good agreement with Rick Field's CDF UE analysis
- choice of PDF set (CTEQ61l vs MSTW LO** (our default))
- Failure of a physically motivated model usually points to more, interesting physics ... colour structure?



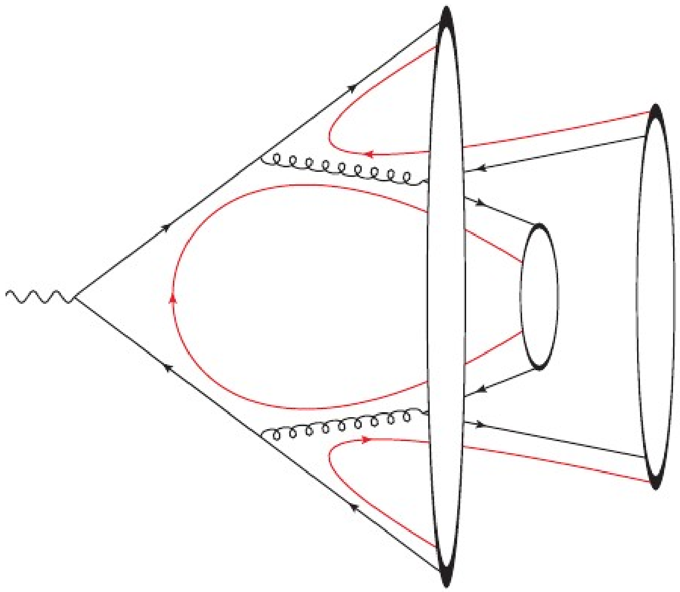
# Colour reconnection (CR) in Herwig



Extending the hadronization model in Herwig(++):

- QCD parton showers provide *pre-confinement* ⇒ colour-anticolour pairs form highly excited hadronic states, the *clusters*

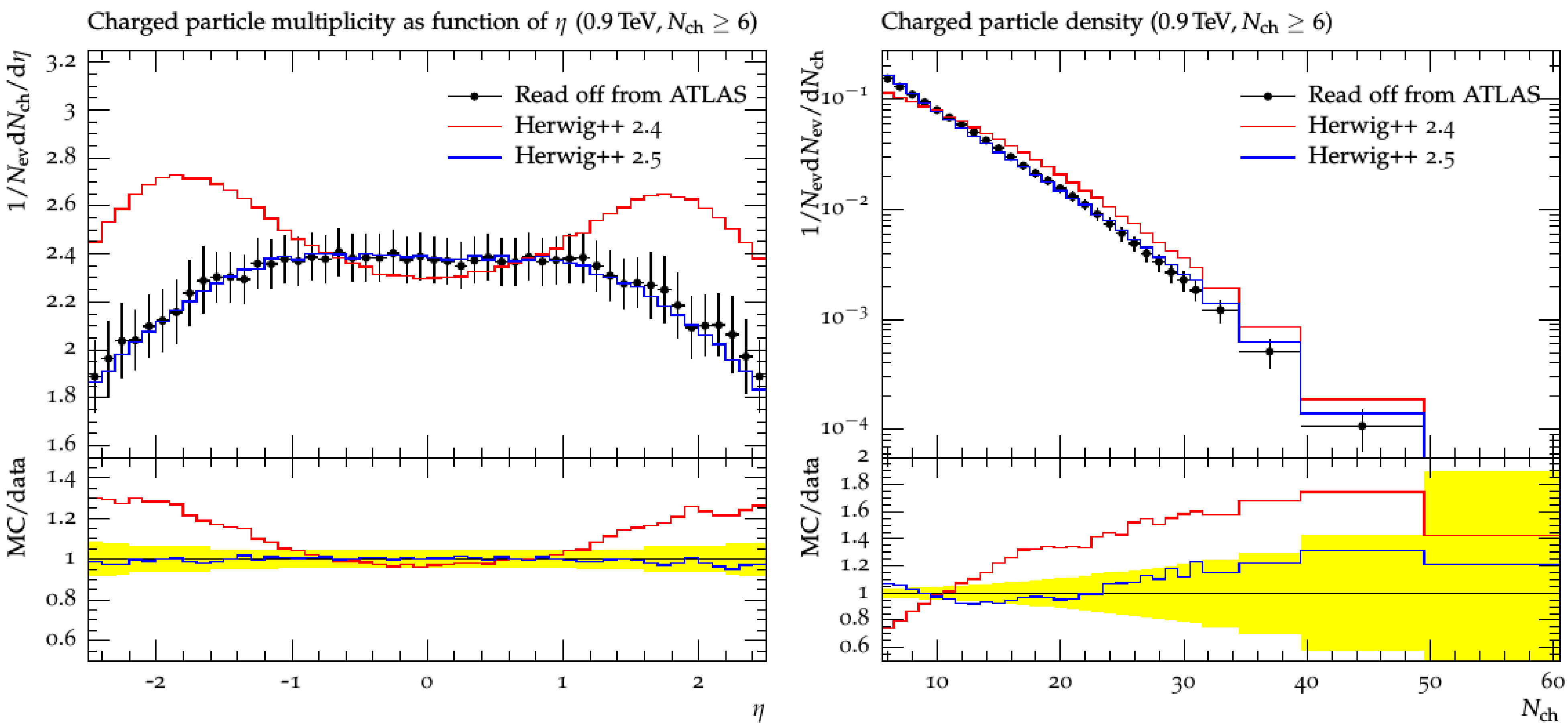
# Colour reconnection (CR) in Herwig



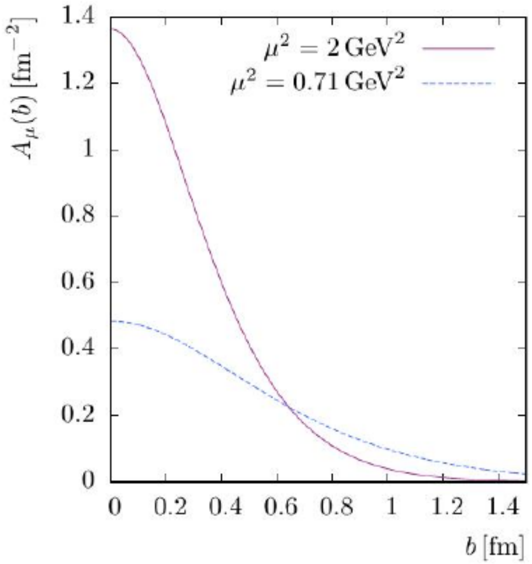
Extending the hadronization model in Herwig(++):

- QCD parton showers provide *pre-confinement* ⇒ colour-anticolour pairs form highly excited hadronic states, the *clusters*
- CR in the cluster hadronization model: allow *reformation* of clusters, *e.g.* $(il) + (jk)$
- Physical motivation: exchange of soft gluons during non-perturbative hadronization phase

# Colour reconnection (CR) in Herwig – Minimum Bias data



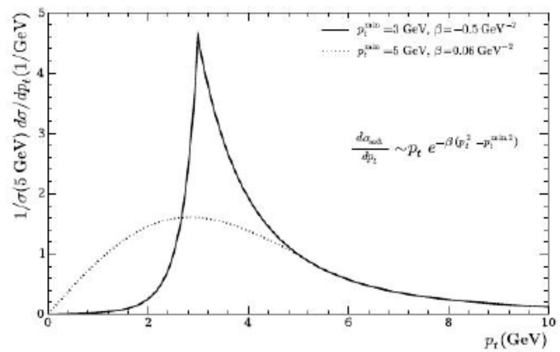
### Matter distribution ($\mu^2$)




Based on electromagnetic form factor

(radius of the proton free parameter)

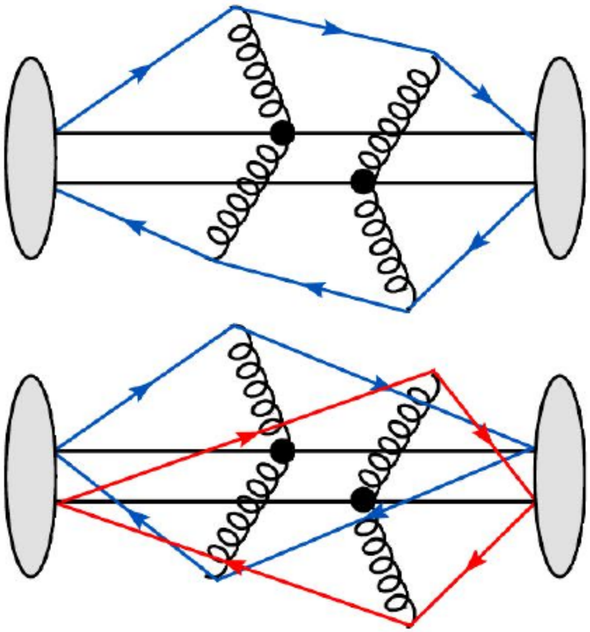
### Extension to soft MPI ($p_t < p_t^{\min}$)




Gaussian extension below $p_t^{\min}$

Energy dependent $p_t^{\min}$

### Colour structure ($p_{reco}$, $p_{CD}$)



Possibility of change of color structure (color reconnection)

The least understood part of modeling

## Main parameters:

- $\mu^2$ - inverse hadron radius squared (parametrization of overlap function)
- $p_t^{\min}$ - transition scale between soft and hard components $\Rightarrow p_t^{\min} = p_{t,0}^{\min}\left(\frac{\sqrt{s}}{E_0}\right)^b$
- $p_{reco}$ - colour reconnection

[Gieseke, Röhr, AS, EPJC C72 (2012)]

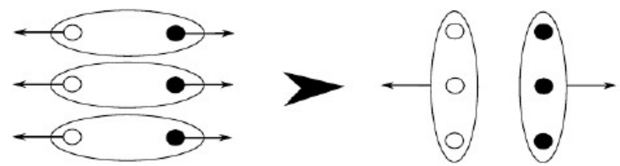
# MPI – recent progress

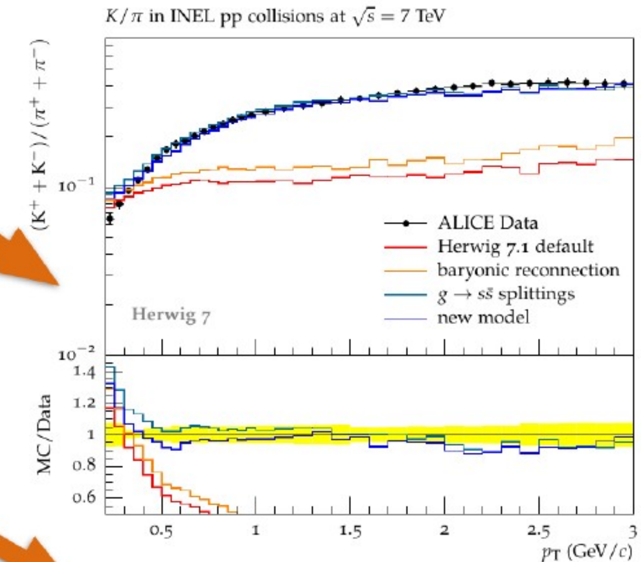
## Baryonic Colour Reconnection

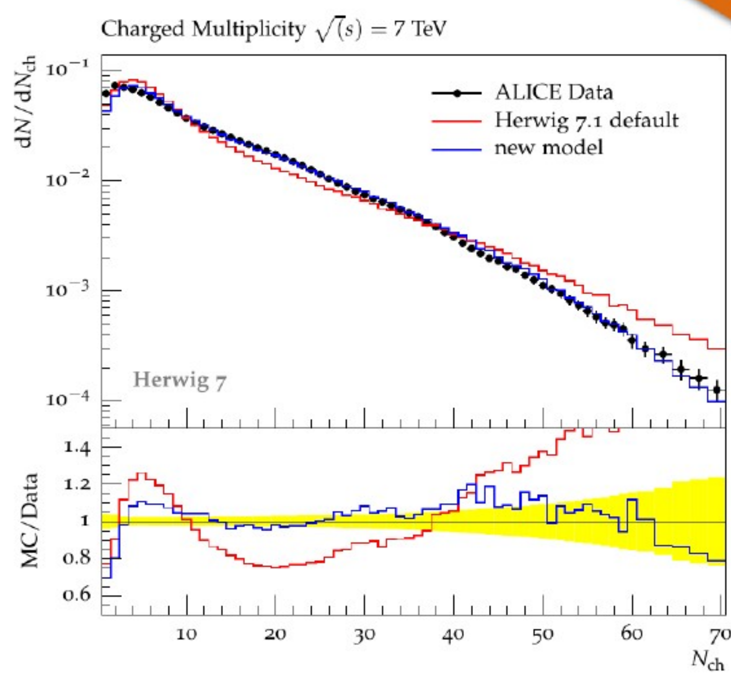
[Gieseke, Kirchgaeßer, Plätzer EPJC 78 (2018) no.2, 99]

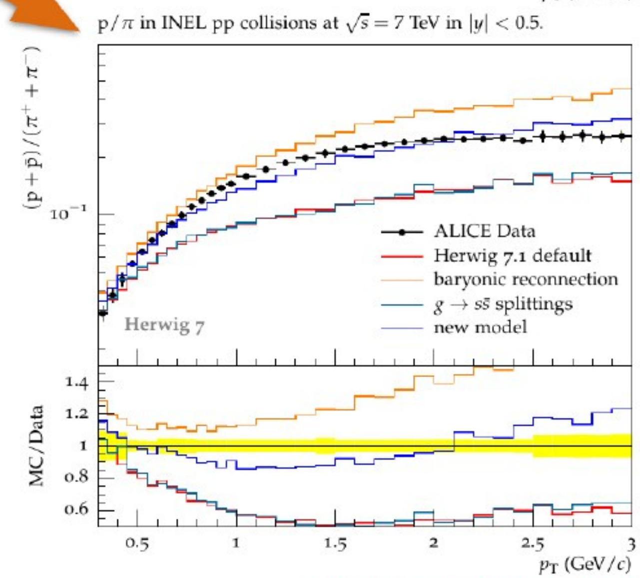
Idea:

- Allow gluon to strange-pairs
- Allow recombination of mesonic to baryonic clusters with probability derived in proximity in momentum space.





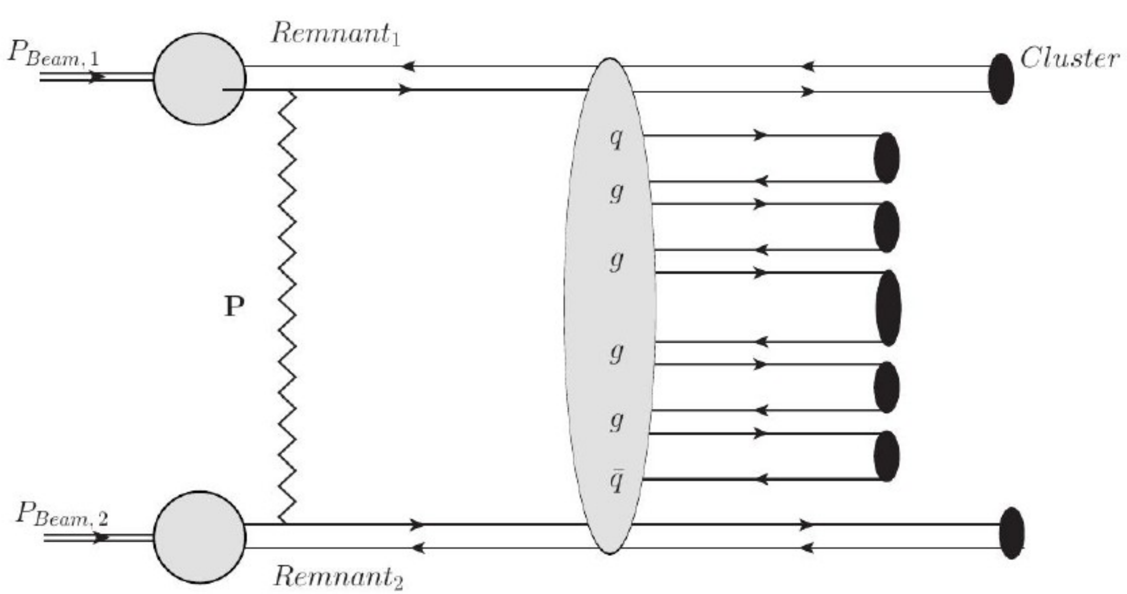



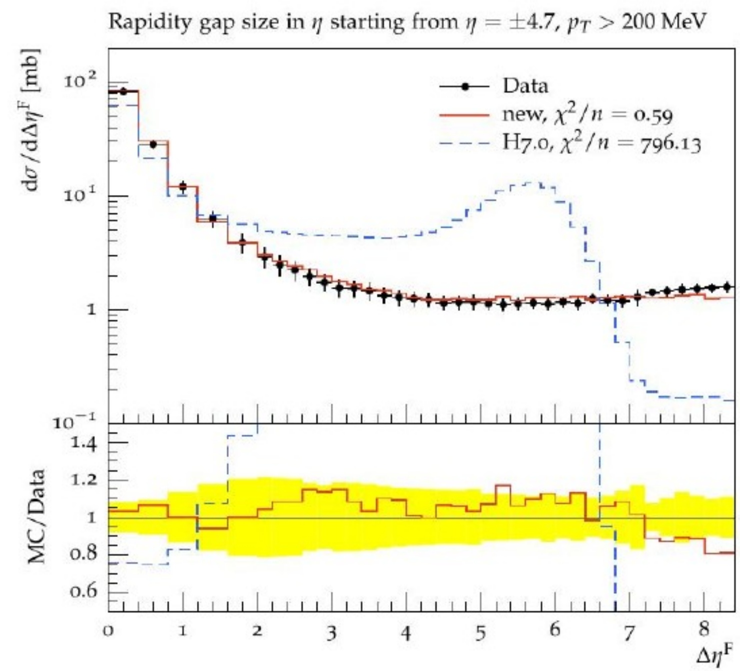

[ALICE, EPJ C75 (2015) 226]

# MPI – recent progress

## Soft Physics

- Inclusion of diffractive topologies
- New soft peripheral MPI model
- The rapidity bump disappears




[S. Gieseke, F. Loshaj, P. Kirchgaeßer Eur.Phys.J. C78 (2018) no.2, 99]

A lot of progress in Soft Physics $\rightarrow$ important to use up-to-date models and tunes!
More is comming:

- Colour Reconnection from Soft Gluon Evolution [S. Gieseke, P. Kirchgaeßer, S. Plätzer, AS arXiv:1808.06770]
- Space-time Colour Reconnection [Bellm, Blok, Duncan, Gieseke, Myska, AS]

# Summary and outlook

- Almost all HEP measurements and discoveries in the modern era have relied on GPMC generators, most notably the discovery of the Higgs boson.
- Complex structure of Quantum Chromodynamics:
  - Perturbative techniques (hard process)
  - Resummation techniques (Parton Shower – well established)
  - Non-perturbative models (crucial to obtain fully exclusive simulation of the collisions)
- Tremendous amount of new developments in GPMCs because we need more

  precise results.
- Constant improvements of MPI models in Herwig
- Good first round of LHC data well described...
- ... but still a lot of space for improvements (collective effects in pp – CR? Hydro? Rope models? Mixture of all the effect?)
- In both the Cosmic Rays and LHC experiments we study the same physics! Space for cross-took and progress!!

# Monte Carlo
training studentships


**3-6 month** fully funded studentships for current PhD students at one of the MCnet nodes. An excellent opportunity to really understand and improve the Monte Carlos you use!

**Application rounds every 3 months.**

MCnet

funded by: MARIE CURIE ACTIONS

for details go to:
**www.montecarlonet.org**

MC*net* projects

Pythia+Vincia

Herwig

Sherpa

MadGraph

"Plugin" – Ariadne+HEJ

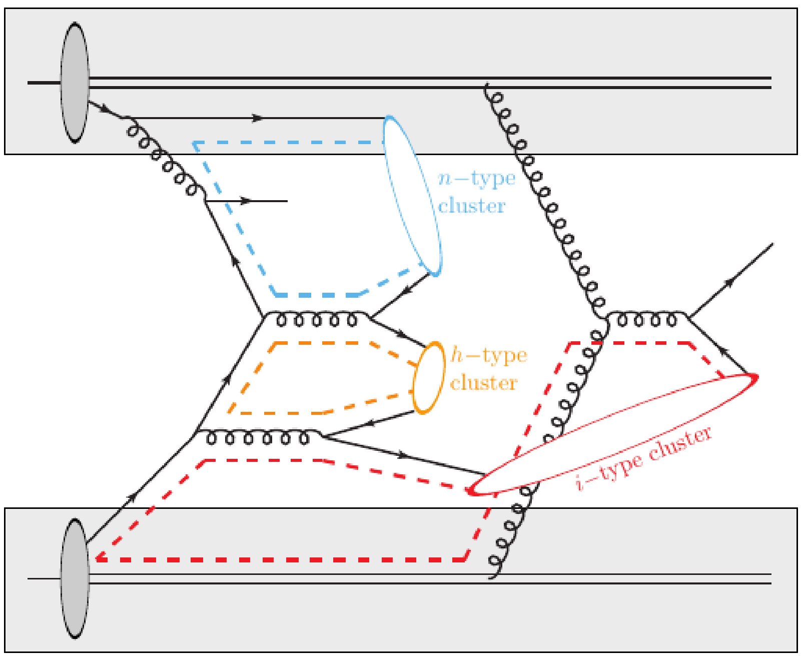
CEDAR – Rivet+Professor

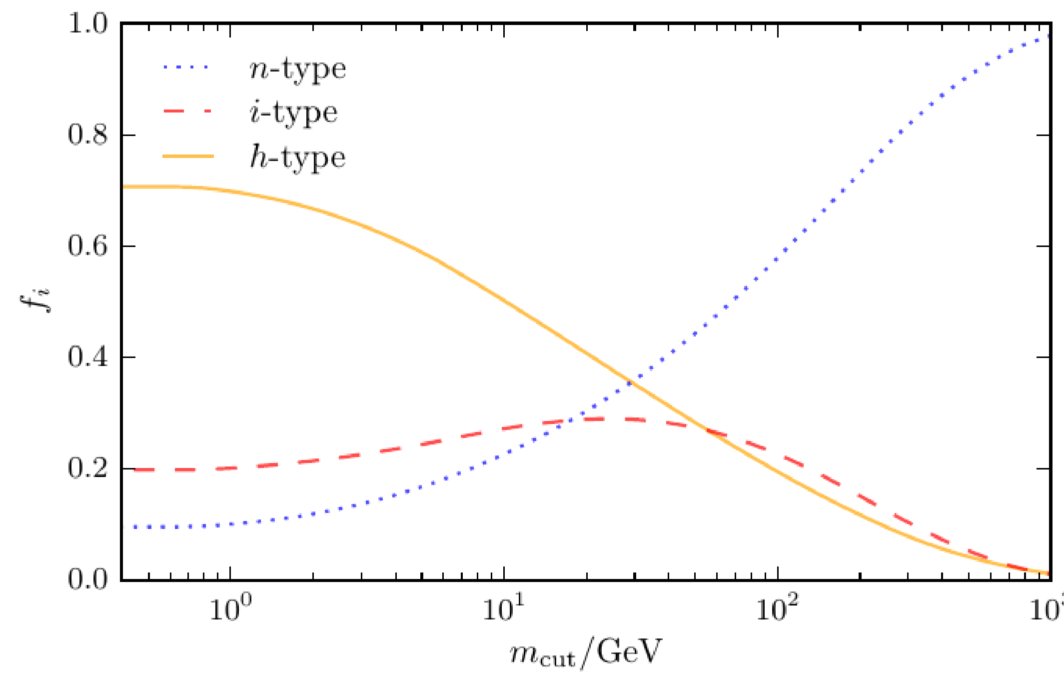
+Contur+hepforge+…

Thank you for your attention!

# MPI – Quiz (CR)

$$f_a(m_{cut}) \equiv N_a(m_{cut}) / \sum_{b=h,i,n} N_b(m_{cut}) = \frac{N_a(m_{cut})}{N_{cl}} , \qquad (1)$$

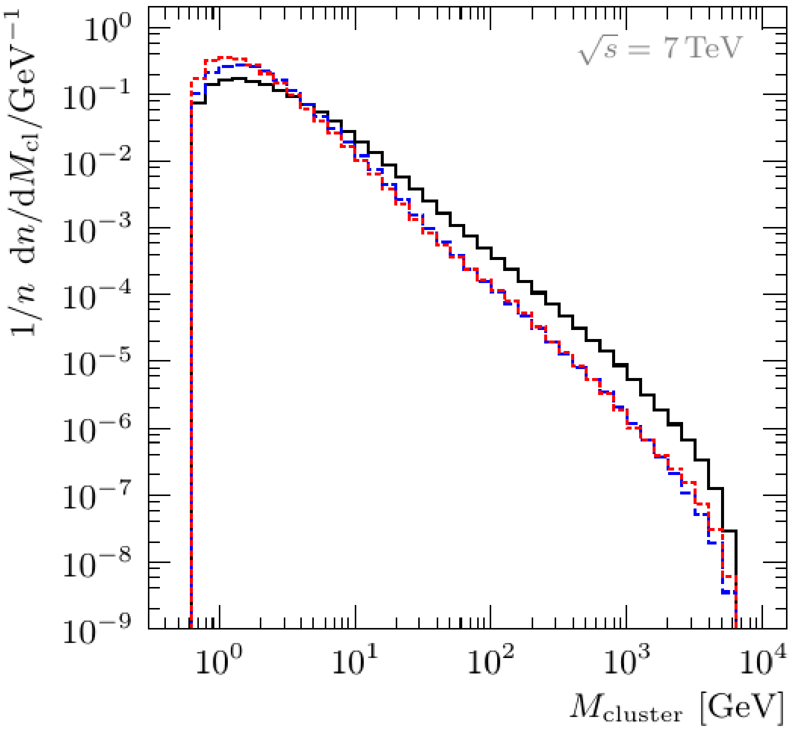


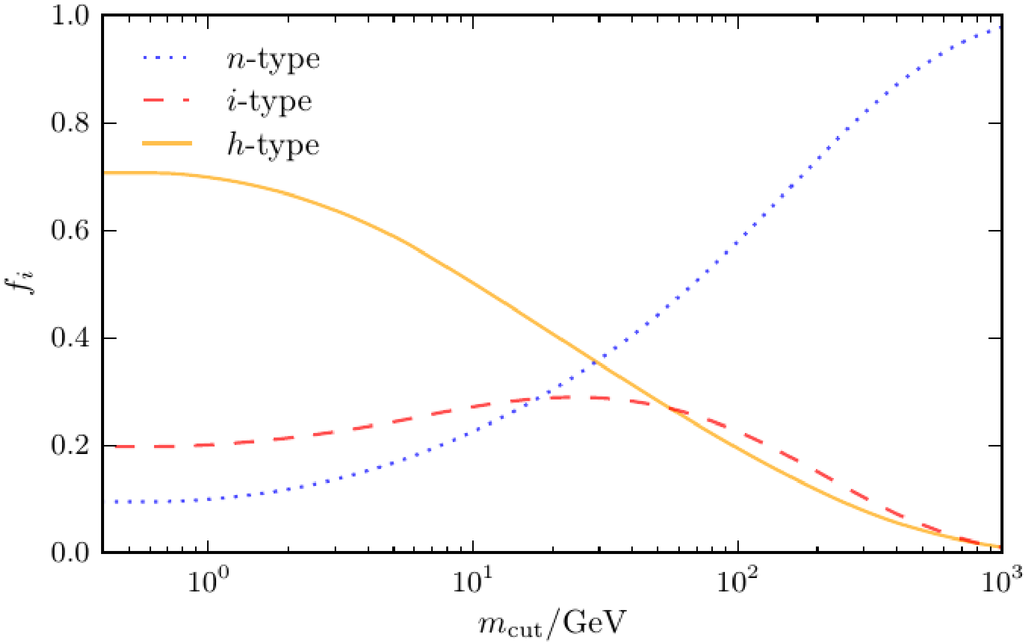




Since these n-clusters can lie at very different rapidities (the extreme case being the two opposite beam remnants), the strings or clusters spanned between them can have very large invariant masses (though normally low *pT*), and give rise to large amounts of (soft) particle production.

# MPI – Quiz (CR)

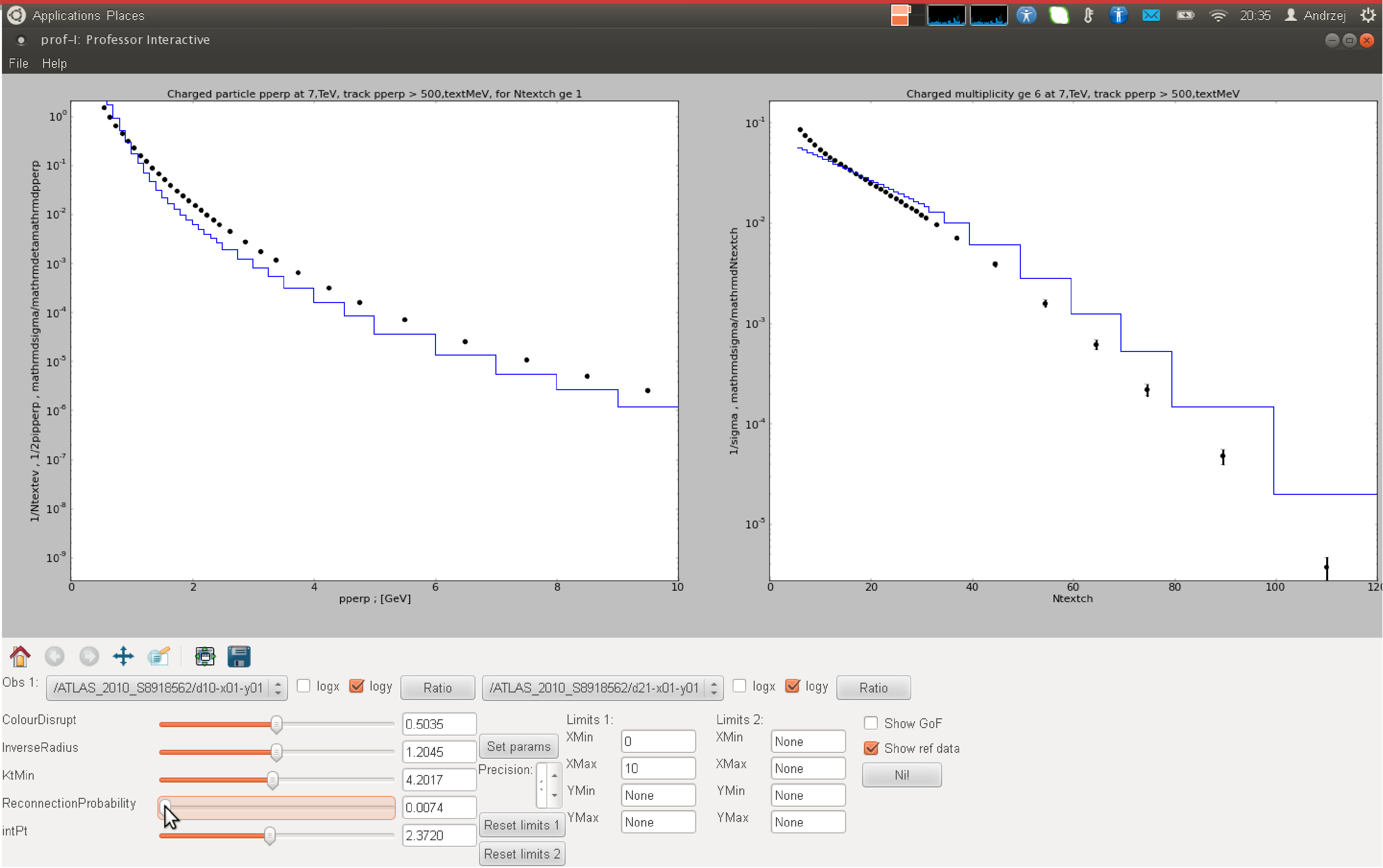
$$f_a(m_{cut}) \equiv N_a(m_{cut}) / \sum_{b=h,i,n} N_b(m_{cut}) = \frac{N_a(m_{cut})}{N_{cl}}, \qquad (1)$$



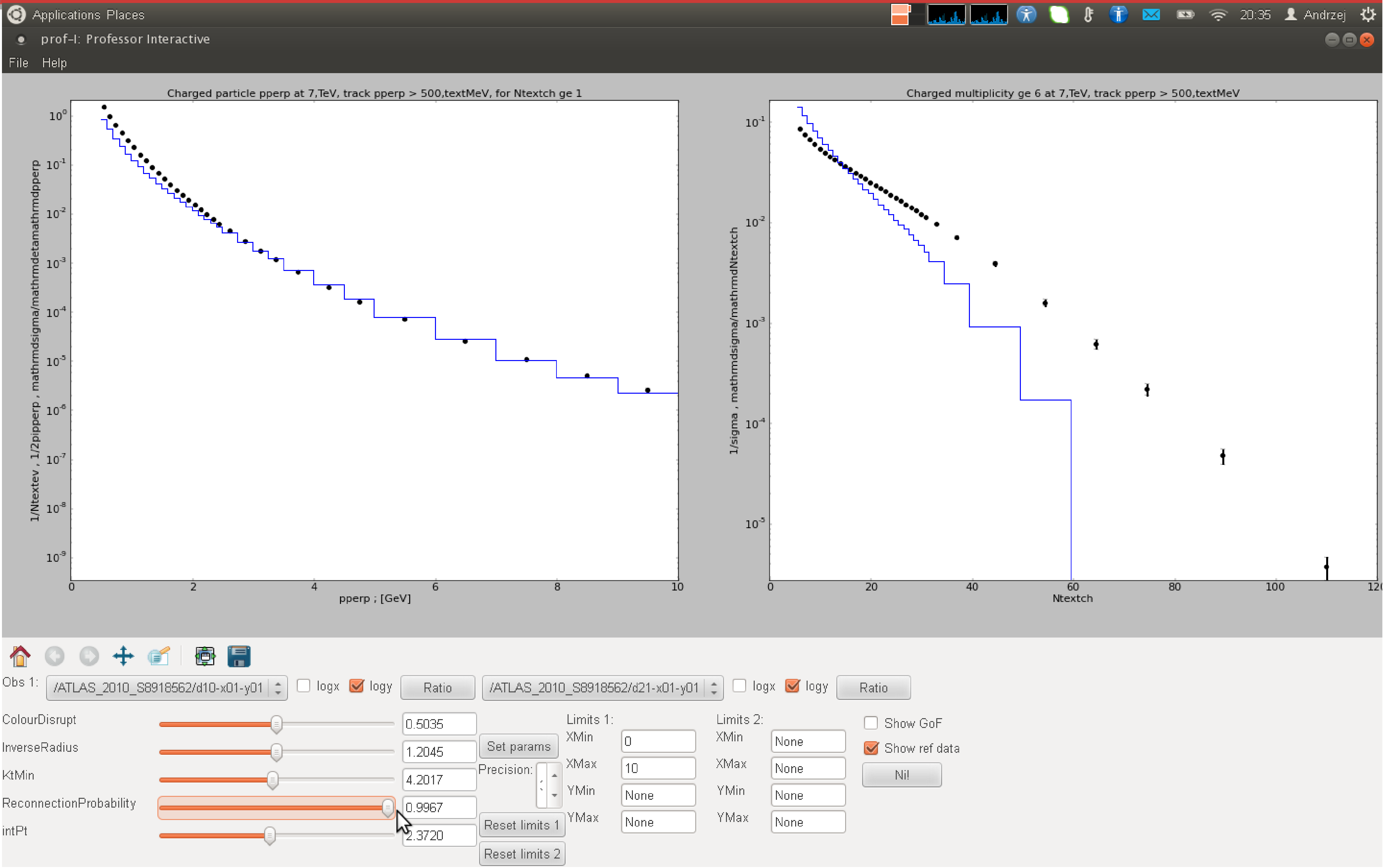




Since these n-clusters can lie at very different rapidities (the extreme case being the two opposite beam remnants), the strings or clusters spanned between them can have very large invariant masses (though normally low *pT*), and give rise to large amounts of (soft) particle production.

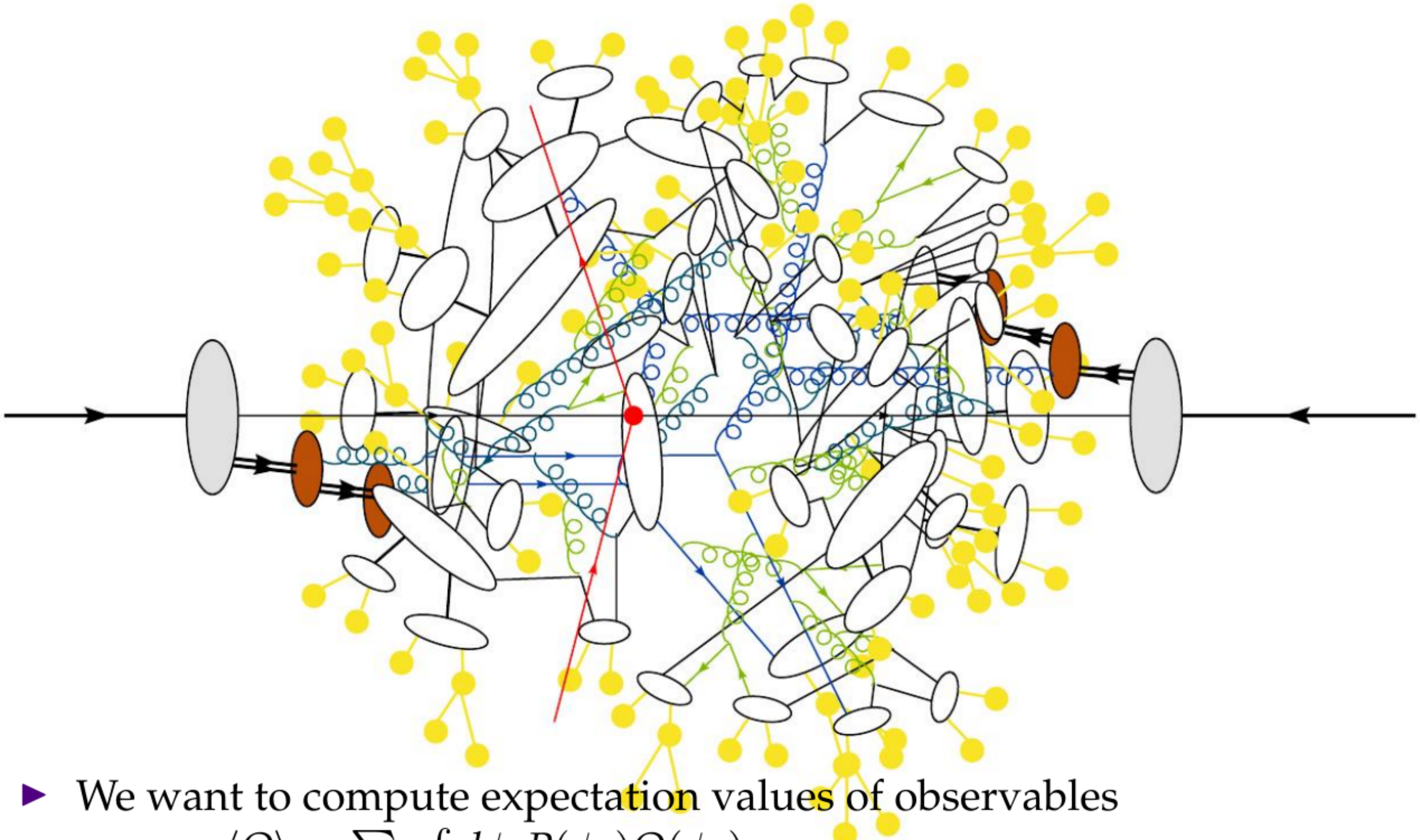
# MPI – Quiz


Applications Places
20:35
Andrzej
prof-I: Professor Interactive
File Help
Charged particle pperp at 7,TeV, track pperp > 500,textMeV, for Ntextch ge 1
1/Ntextev , 1/2pipperp , mathrmdsigma/mathrmdetamathrmdpperp
pperp ; [GeV]
Charged multiplicity ge 6 at 7,TeV, track pperp > 500,textMeV
1/sigma , mathrmdsigma/mathrmdNtextch
Ntextch
Obs 1:
/ATLAS_2010_S8918562/d10-x01-y01
logx
logy
Ratio
/ATLAS_2010_S8918562/d21-x01-y01
logx
logy
Ratio
ColourDisrupt
0.5035
InverseRadius
1.2045
KtMin
4.2017
ReconnectionProbability
0.0074
intPt
2.3720
Set params
Precision:
Reset limits 1
Reset limits 2
Limits 1:
XMin 0
XMax 10
YMin None
YMax None
Limits 2:
XMin None
XMax None
YMin None
YMax None
Show GoF
Show ref data
Ni!

# MPI – Quiz


Applications Places
20:35
Andrzej
prof-I: Professor Interactive
File
Help
Charged particle pperp at 7,TeV, track pperp > 500,textMeV, for Ntextch ge 1
1/Ntextev , 1/2pipperp , mathrmdsigma/mathrmdetamathrmdpperp
pperp ; [GeV]
Charged multiplicity ge 6 at 7,TeV, track pperp > 500,textMeV
1/sigma , mathrmdsigma/mathrmdNtextch
Ntextch
Obs 1:
/ATLAS_2010_S8918562/d10-x01-y01
logx
logy
Ratio
/ATLAS_2010_S8918562/d21-x01-y01
logx
logy
Ratio
ColourDisrupt
0.5035
InverseRadius
1.2045
KtMin
4.2017
ReconnectionProbability
0.9967
intPt
2.3720
Set params
Precision:
Reset limits 1
Reset limits 2
Limits 1:
XMin
0
XMax
10
YMin
None
YMax
None
Limits 2:
XMin
None
XMax
None
YMin
None
YMax
None
Show GoF
Show ref data
Nil

# Monte Carlo methods why and how?



- We want to compute expectation values of observables
  $$\langle O \rangle = \sum_n \int d\phi_n P(\phi_n) O(\phi_n),$$
  where $\phi_n$ - Point in n-particle phase-space, $P(\phi_n)$ Probability to produce $\phi_n$, Value of observable at $O(\phi_n)$.
- large $n$ $\mathcal{O}(100 \div 1000) \Rightarrow$ Monte Carlo is the only choice.

# Monte Carlo methods why and how?

$$\langle O \rangle = \sum_n \int d\phi_n P(\phi_n) O(\phi_n)$$

Problems:

- Integrate a multi dimensional function

Efficiencies of integration methods (MC with numerical quadrature):

| Uncertainty as a function of number of points $n$ | In 1 dim. | In $d$ dim. |
|---|---|---|
| Monte Carlo | $n^{-1/2}$ | $n^{-1/2}$ |
| Trapezoidal rule | $n^{-2}$ | $n^{-2/d}$ |
| Simpson's rule | $n^{-4}$ | $n^{-4/d}$ |

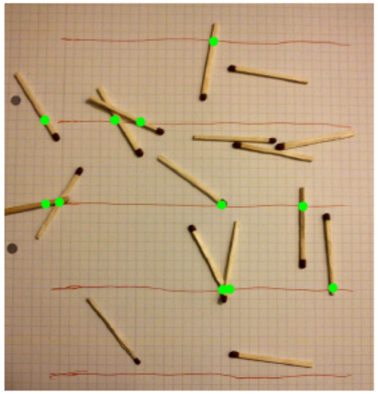
- Pick a point at random according to a probability distribution.

## Wikipedia

Monte Carlo methods are a broad class of computational algorithms that rely on repeated random sampling to obtain numerical results.

History:

- G. Comte de Buffon (1777) – perhaps the earliest documented use of random sampling to find the solution to the integral (by throwing a needle onto horizontal plane ruled with straight lines).
- Marquis Pierre-Simon de Laplace (1886) – use of Buffon's method to evaluate $\pi$.

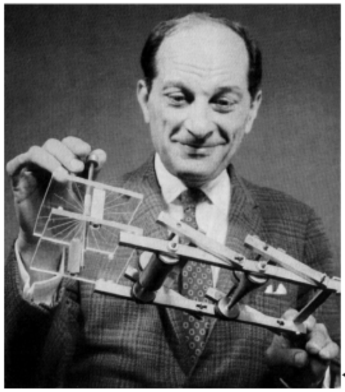


Calculate $\pi$ by dropping a needle onto the floor.
$\Leftarrow 34/11 \sim 3.1$ based on 17 throws

- Lord Kelvin (1901) – use random sampling (drawing numbered pieces of paper from a bowl) to aid in evaluating some integrals in the kinetic theory of gases.

## History – cont.

- Enrico Fermi (1930s) – numerical sampling experiments on neutron diffusion and transport in nuclear reactors (deviced FERMIAC – a mechanical sampling device).



← S. Ulam with FERMIAC

- J. von Neumann, S. Ulam, N. Metropolis, R. Feynman (1940s) – first large-scale random-numbers based calculations of neutron scattering and absorption during the "Manhattan" project (work on a nuclear bomb). Name Monte Carlo refers to the Monte Carlo Casino in Monaco where Ulam's uncle would borrow money from relatives to gamble.
- ...
- In Particle Physics we have to solve multidimensional integrals (many particles) MC methods very efficient! So we play a roulette to understand the law of the nature :)