Jet counting & QCD scaling patterns

Peter Schichtel
@ IMPRS-PTFS seminar 2013

based on:
Englert, P.S., Schumann, Plehn: Phys.Rev. D83 (2011) 095009
Gerwick, Schumann, Plehn: Phys.Rev.Lett. 108 (2012) 032003
Englert, P.S., Schumann, Plehn: JHEP 1202 (2012) 030
Gerwick, P.S., Schumann, Plehn: JHEP 1210 (2012) 162
Gerwick, Gripaios, Schumann, Webber: JHEP 1304 (2013) 089
and still some stuff to come ...

jets?

jets are a collimated spray of hadrons

jet algorithm

distance measure [e.g. k_T algorithm]

1.) $y_{ij} = \frac{\Delta R_{ij}}{R} \min\left(p_{T,i}^2, p_{T,j}^2\right)$

2.) $y_{iB} = p_{T,i}^2$

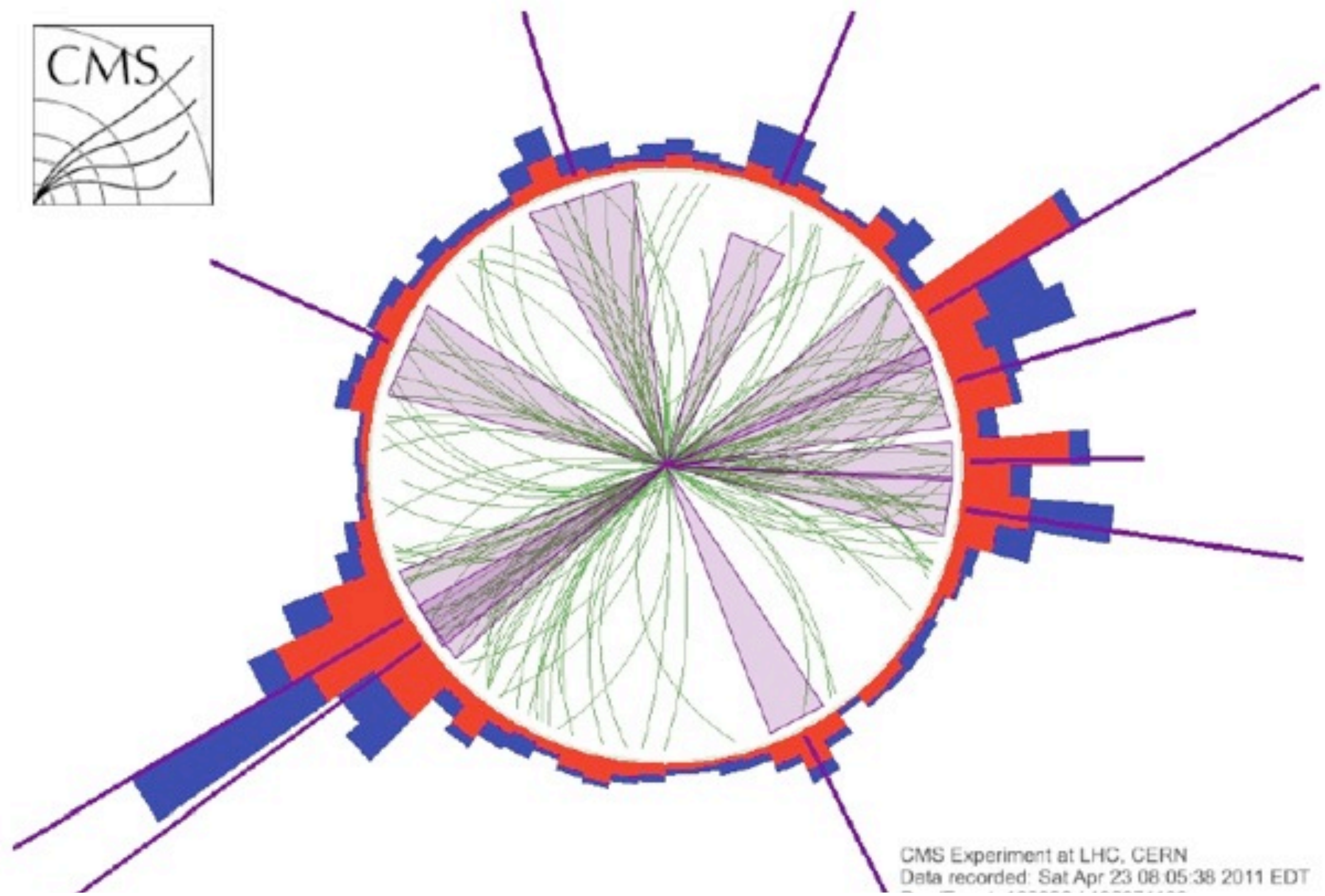
clustering scheme:

1.) smallest → cluster i and j

2.) smallest → call it a jet

i and j can be anything: particles, detector cells, partons,...

[CMS multi-jet event →]



many algorithms, different parameters yield different jets

why jets?

LHC is a discovery machine: Higgs(✔), BSM(?)

LHC is a SM machine: precision test

proton collider: QCD machine

this talk is all about LHC physics

physics processes:

→ Drell-Yan [Z plus jets, mirror process to e+e-]

→ WBF Higgs [tagging jets]

→ strong coupling [2 vs. 3 jets]

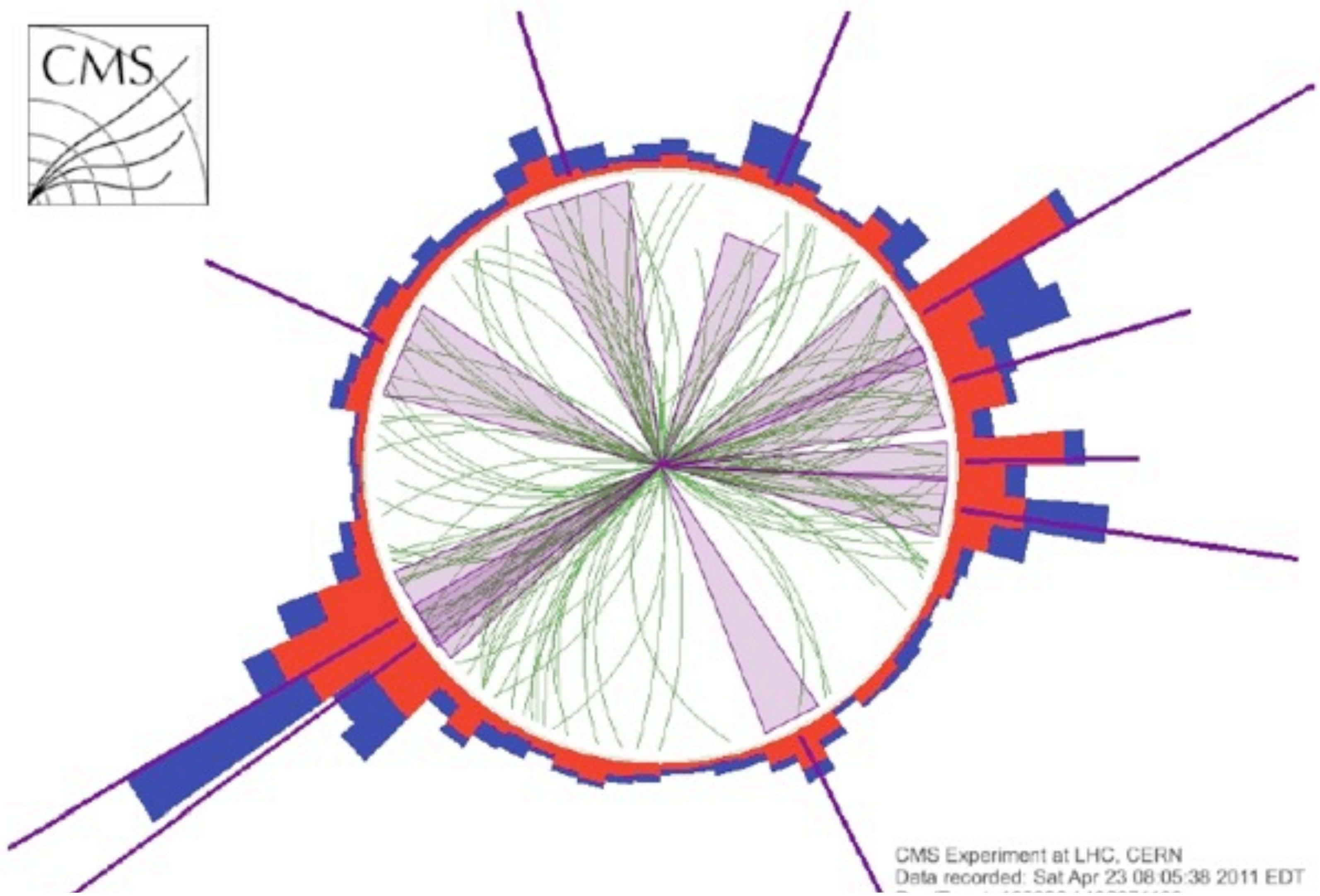
→ di-jet resonances [new physics]

backgrounds:

→ W/Z plus jets [Higgs, missing energy]

→ top plus jets [decay chains, missing energy]

→ pure QCD jets [fake missing energy]



[CMS multi-jet event →]

understanding jets is essential for LHC physics

LHC physics

Experiments:

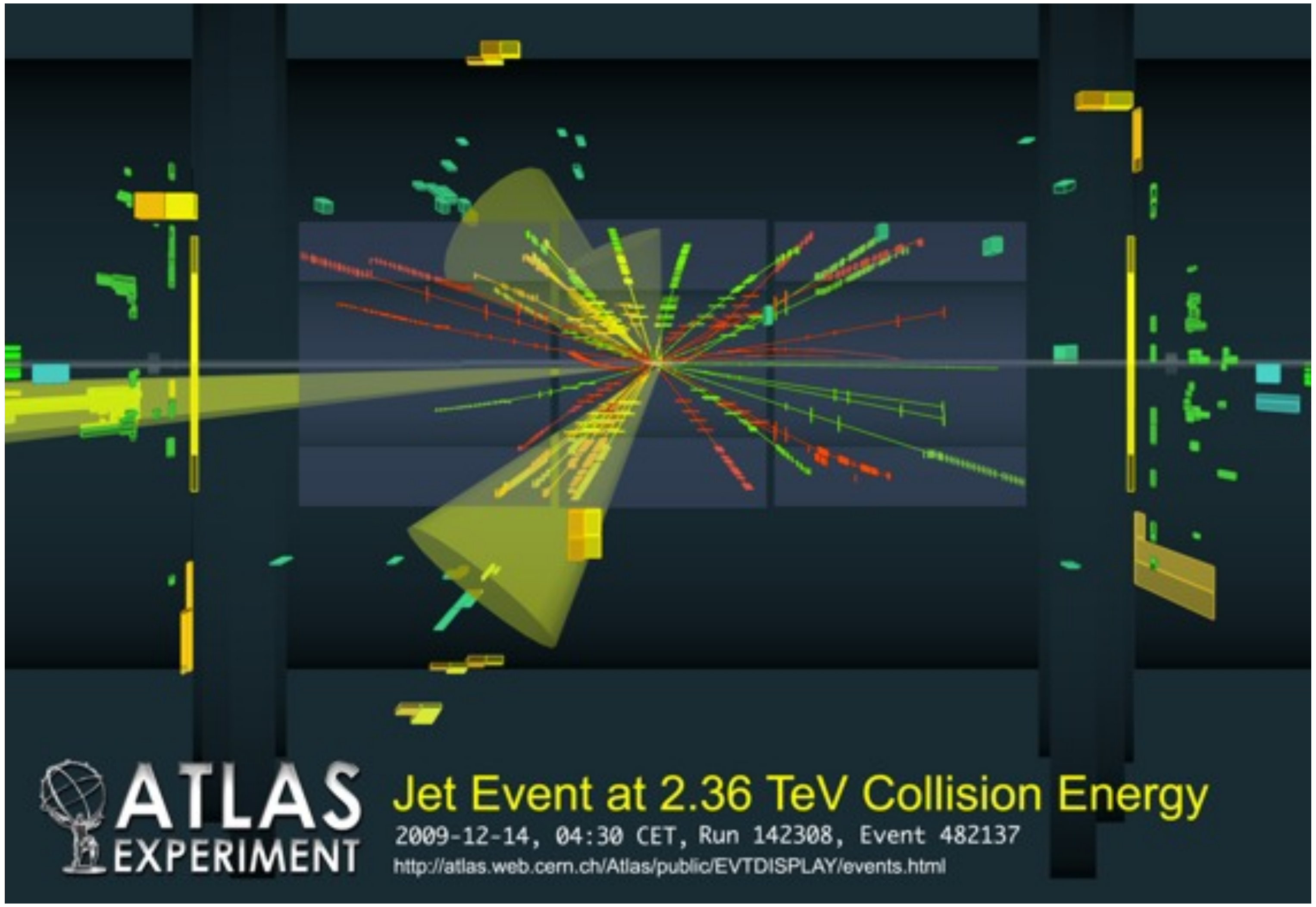
a theorists point of view

what kind of information?

tracks
particle flow
calorimeter cells

jet algorithm ↓

jets → cross sections



sources of uncertainty:
→ systematics
→ statistcs

LHC physics

Theory:

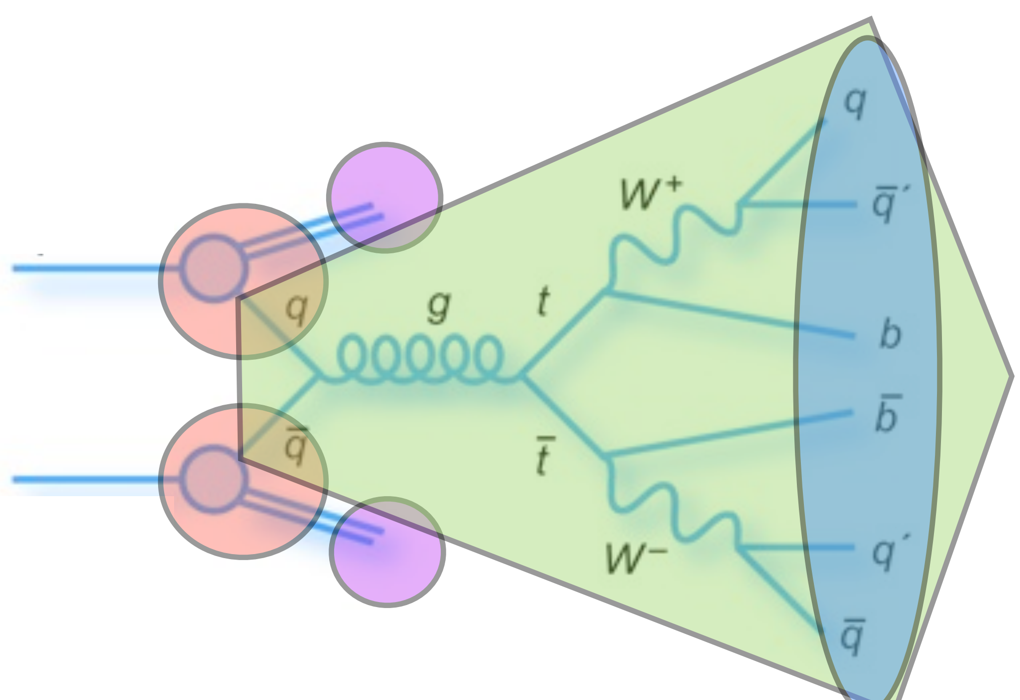
total cross section

partonic cross section (LO, NLO, ...)

$$\sigma^{pp\to P+X}_{\mathrm{LHC}}(\sqrt{s},\mu_F,\mu_R) = \sum_{a,b}\int dx_a dx_b\, f_p(x_a,\mu_F)\, f_p(x_b,\mu_F)\, \hat{\sigma}^{ab\to P}(x_a,x_b,\sqrt{s},\mu_F,\mu_R)\times F^{\mathrm{cuts}}_{\mathrm{soft}}$$

PDFs

hadronization, event cuts, ...



[from: fnal.gov/Run2Physics]

master equation is inclusive: n + X jets

sources of uncertainty:
→ PDFs
→ factorization scale

jet counting

inclusive: at least n jets

→ easily calculable

→ n jets in matrix element

→ PDF's sum collinear radiation X

→ higher order leads to smaller uncertainty

exclusive: exactly n jets

→ excl. jet rates are ambiguous (ISR?)

→ closer to real event structure

→ statistical independent

→ correlation to other multi-jet observables

analysis	# excl. jets
Higgs WBF	0,1,2
Higgs WW*	2
di-boson	0,1
top mass	4
new physics	4,8,n(?)

count exclusive jets

use exclusive jet cross-section ratios

jets are counted in addition to the hard event

observe two different patterns: staircase and Poisson scaling

scaling patterns

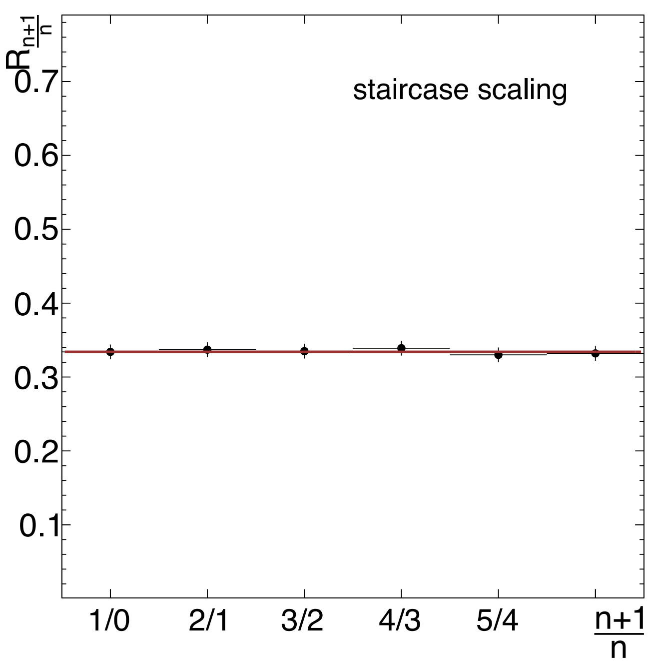
staircase scaling

[Steve Ellis,Kleis,Stirling(1985);Berends(1989)]

$$\sigma_n^{\text{excl.}} = \sigma_0 e^{-bn}$$

constant ratios

$$R_{\frac{n+1}{n}} = \frac{\sigma_{n+1}}{\sigma_n} = R_0$$



[idealized example]

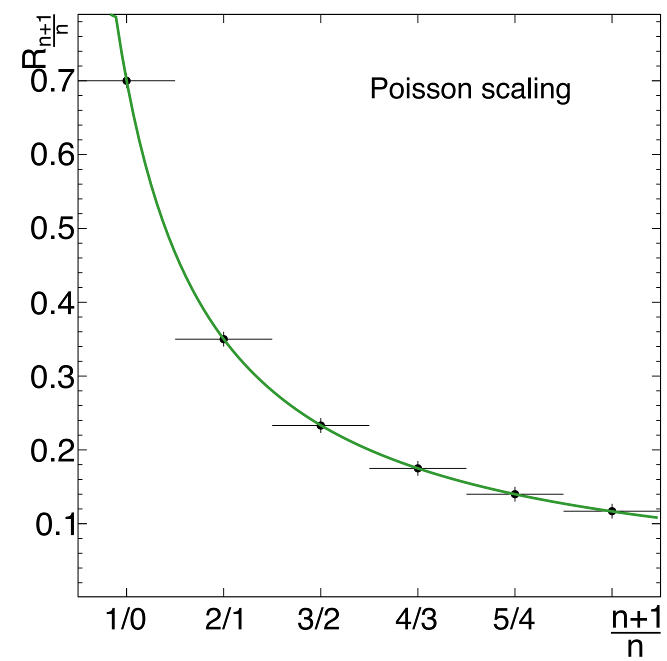
Poisson scaling

[Peskin & Schroeder; Rainwater, Zeppenfeld(1997)]

$$\sigma_n^{\text{excl.}} = \sigma_0 \frac{\bar{n}^n e^{-\bar{n}}}{n!}$$

falling ratios

$$R_{\frac{n+1}{n}} = \frac{\sigma_{n+1}}{\sigma_n} = \frac{\bar{n}}{n+1}$$



[idealized example]

evidenve: UA1, LEP, Tevatron, LHC

the same for inclusive! [NLO]

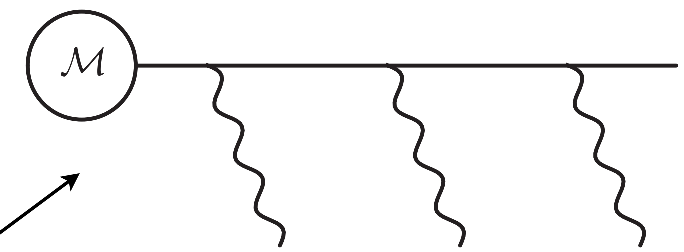
rates depend on jet algorithm and hard process features NOT!

theory behind QCD scaling

eikonal approximation

$$\gamma^\mu \frac{\not{q} + \not{k}}{(q+k)^2} \to \frac{q^\mu}{qk}$$

QED:



n independet emissions

factorization

$$d\sigma_{n+1} = d\sigma_n \times \frac{dt}{t} dz \frac{\alpha_s}{2\pi} P_{i\to jl}(z)$$

probability

$$P(n) = \frac{\bar{n}^n e^{-\bar{n}}}{n!}$$

normalization

bosonic phase space

Sudakov form factor: non splitting prob.

splitting kernel → integrate

$$\Delta_i(t) = \exp\left[-\int_{t_0}^{t} dt' \sum_{jl} \Gamma_{i\to jl} \right]$$

three gluon vertex → secondary emissions

QCD:

factorization still holds

→ resummation

→ parton shower

→ iterated Poisson

theory behind QCD scaling

generating functional formalism

jet rate

$$\Phi(u) := \sum_n u^n P(n) \qquad P(n) = \frac{1}{n!}\frac{d^n}{du^n}\Phi(u)\Big|_{u=0}$$

electron collider: Durham algorithm

$$y_{ij} = 2\,\min\left(E_i^2, E_j^2\right)\frac{1-\cos\,\theta_{ij}}{t}$$

scale of hard process

jet resolution

$$y_{\rm cut} = \frac{t_0}{t}$$

smallest resolvable splitting

evolution equation

[time like evolution]

$$\Phi_i(t) = u\,\exp\left[\int_{t_0}^{t} dt' \sum_{jl}\Gamma_{i\to jl}\left(\frac{\Phi_j(t')\Phi_l(t')}{\Phi_i(t')} - 1\right)\right]$$

simultaneous evolution in energy and distance

$$t = 2E_iE_j(1-\cos\,\theta_{ij})$$

theory behind QCD scaling

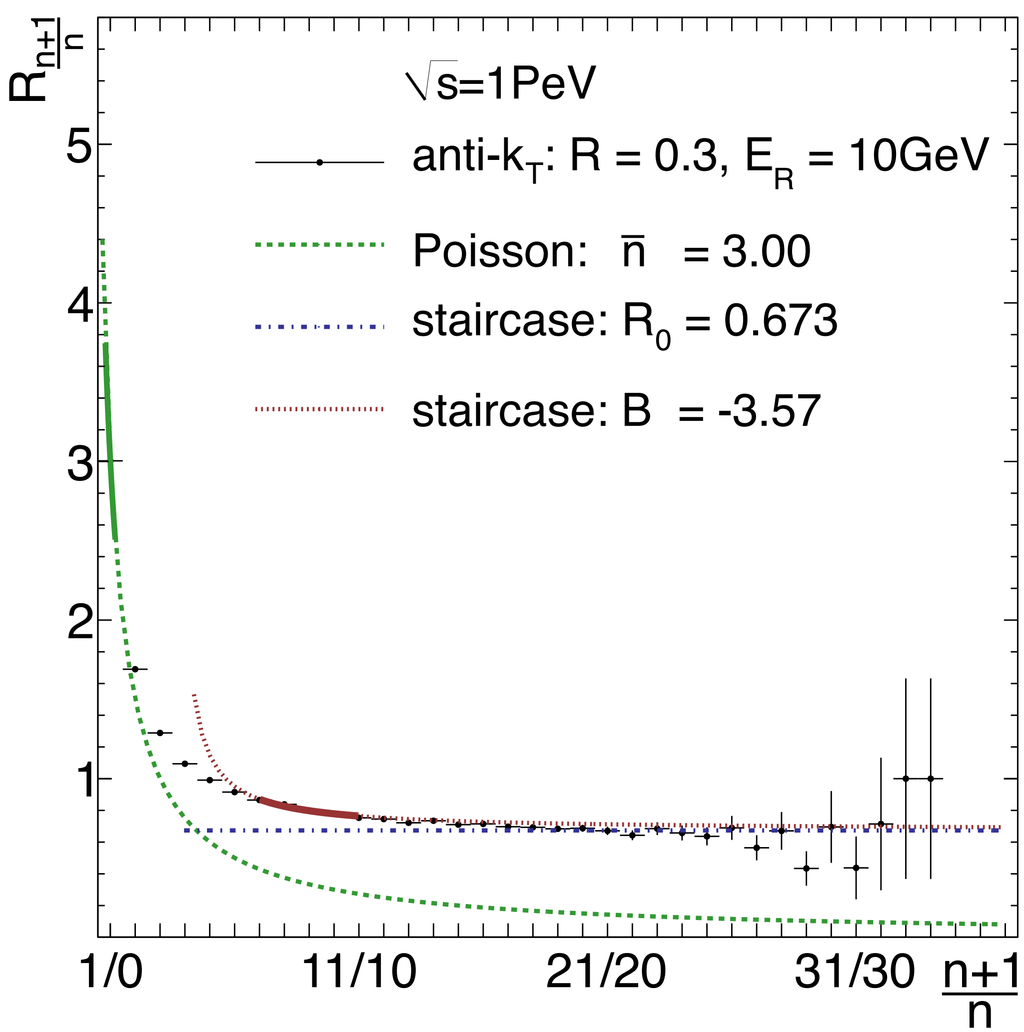
large log limit: $t \gg t_0$ — primary emissions dominate → Poisson scaling

democratic limit $t \to t_0$ — exact solution
first time! [JHEP 1210 (2012) 162]

$$\Phi_g(t) = \frac{1}{1 + \frac{1-u}{u\Delta_g(t)}}$$

→ staircase scaling

$$R_{\frac{n+1}{n}} := \frac{P(n+1)}{P(n)} = 1 - \Delta_g(t)$$



← simulation of $e^+e^- \to q\bar{q} + n \times g$

generalized k_T algorithm:
→ independent evolution in energy and distance
[JHEP 1304 (2013) 089]

new

compute staircase scaling breaking terms

$$R_{\frac{n+1}{n}} = (1 - \Delta_g(t)) \left[1 + \frac{1}{B + (n+1)}\right]$$

excpected to be negative

hadron collider effects

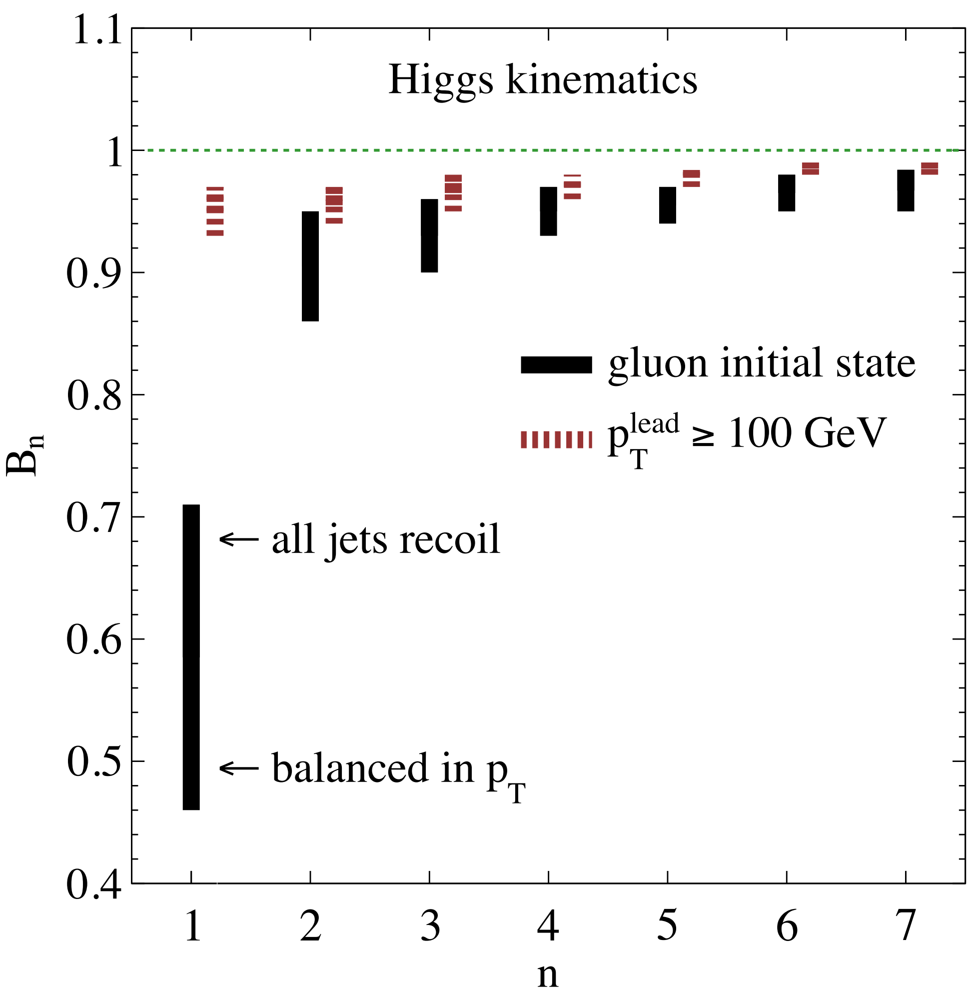
at leading log pdfs and jet evolution factorize

assume threshold kinematics

pdf effects on jet ratios

$$x^{(0)} \approx \frac{m_Z}{2E_{\text{beam}}} \qquad x^{(1)} \approx \frac{\sqrt{m_Z^2 + 2\left(p_T\sqrt{p_T^2+m_Z^2}+p_T^2\right)}}{2E_{\text{beam}}}$$

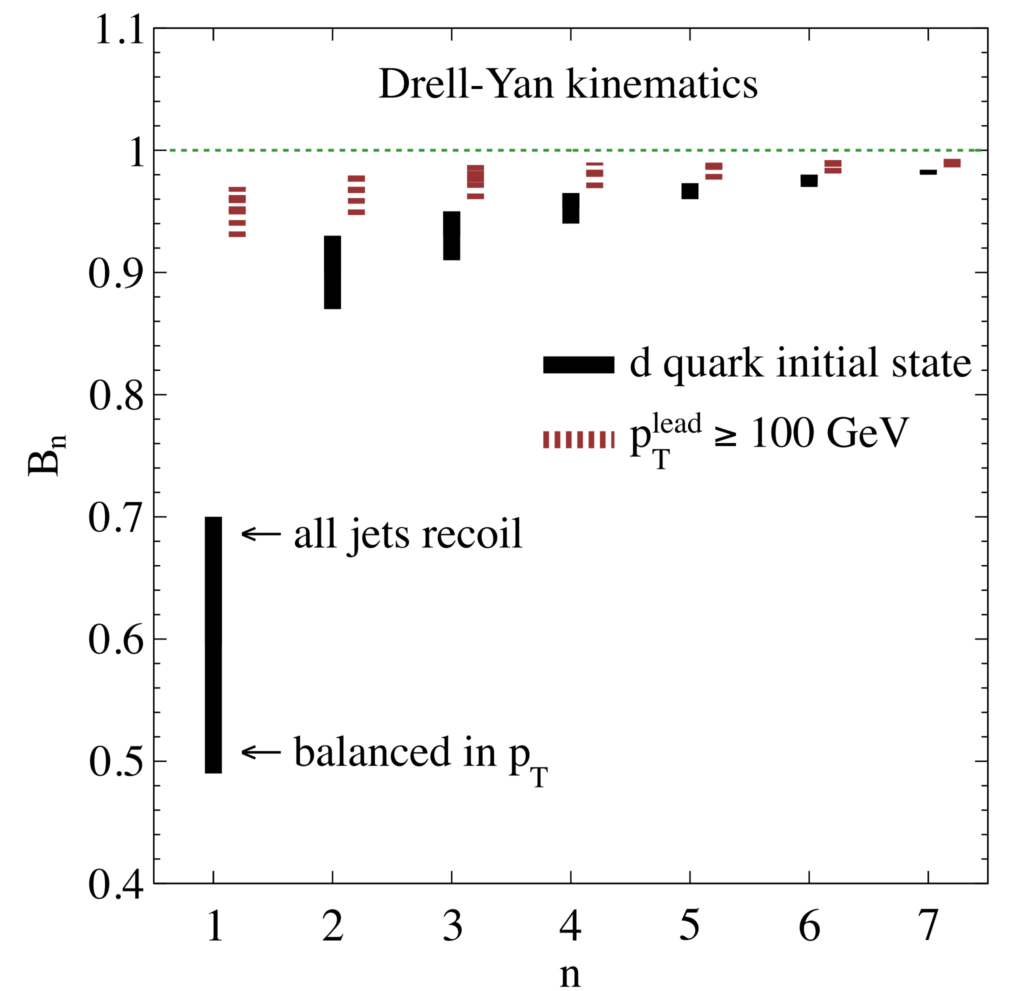
$$B_n = \left|\frac{\frac{f(x^{(n+1)},Q)}{f(x^{(n)},Q)}}{\frac{f(x^{(n+2)},Q)}{f(x^{(n+1)},Q)}}\right|^2$$



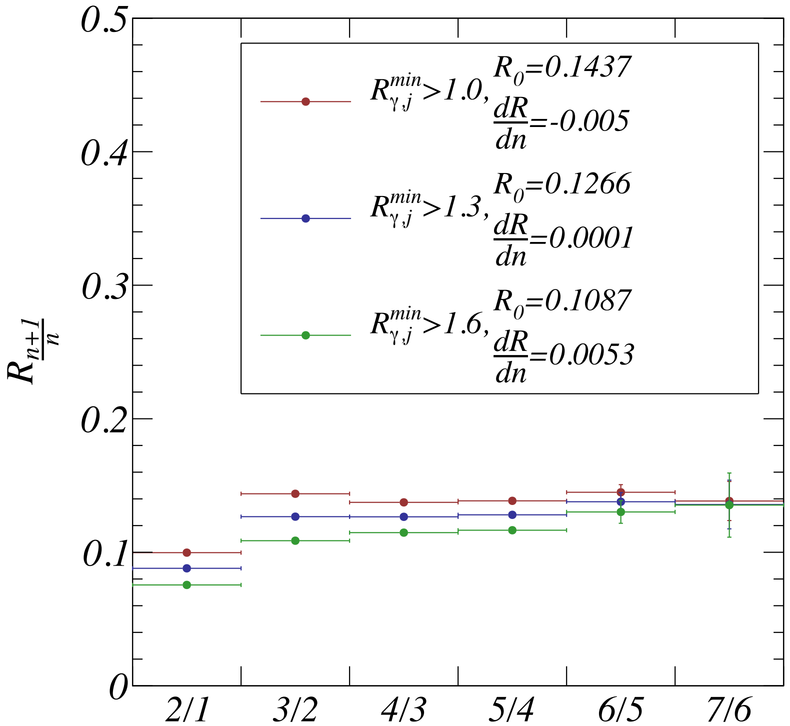
suppression of low n

[JHEP 1210 (2012) 162]

sweet spot



learn, test, ...

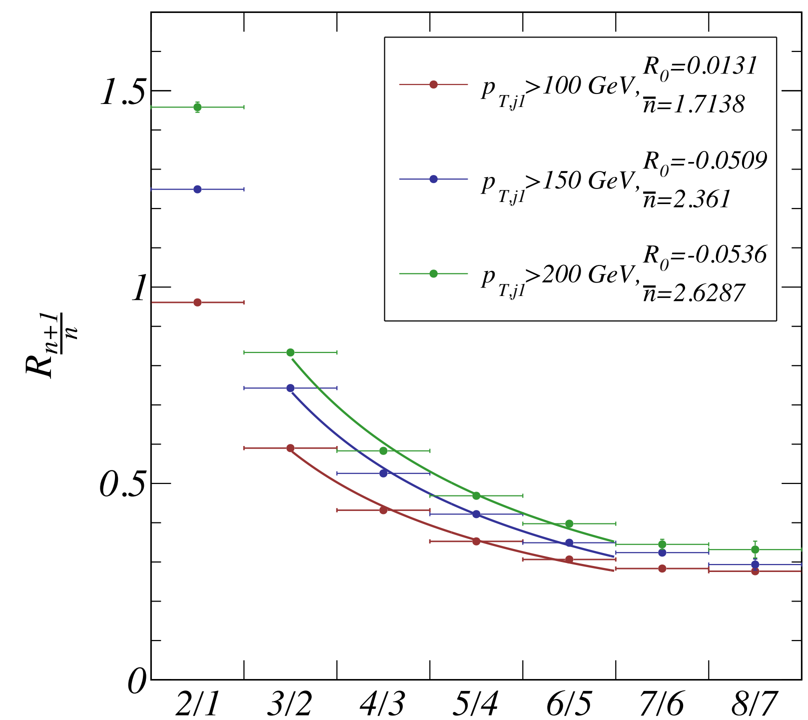


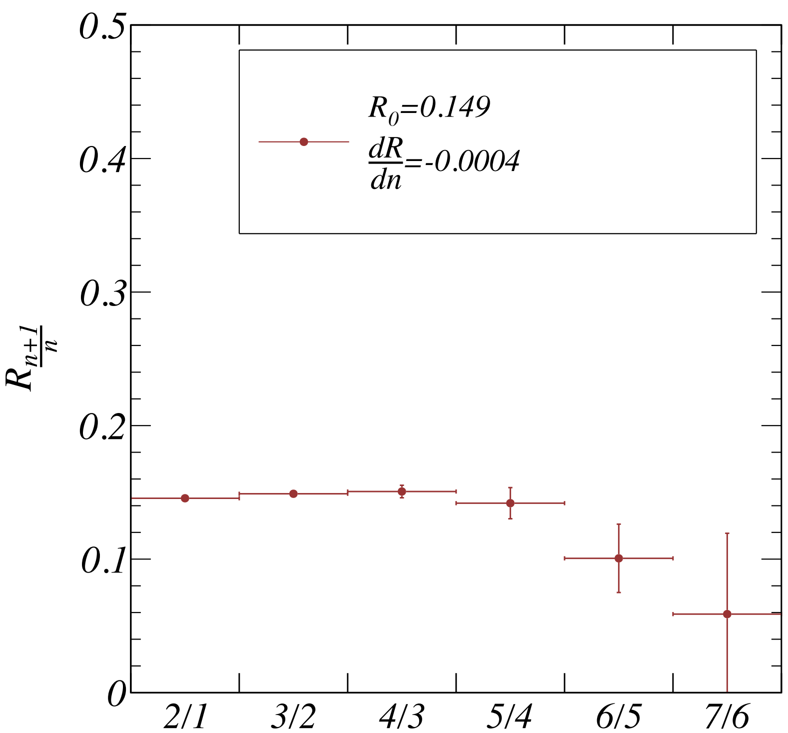
photon plus jets

high cross-section: signal free

tune between patterns

→ understand experimentally



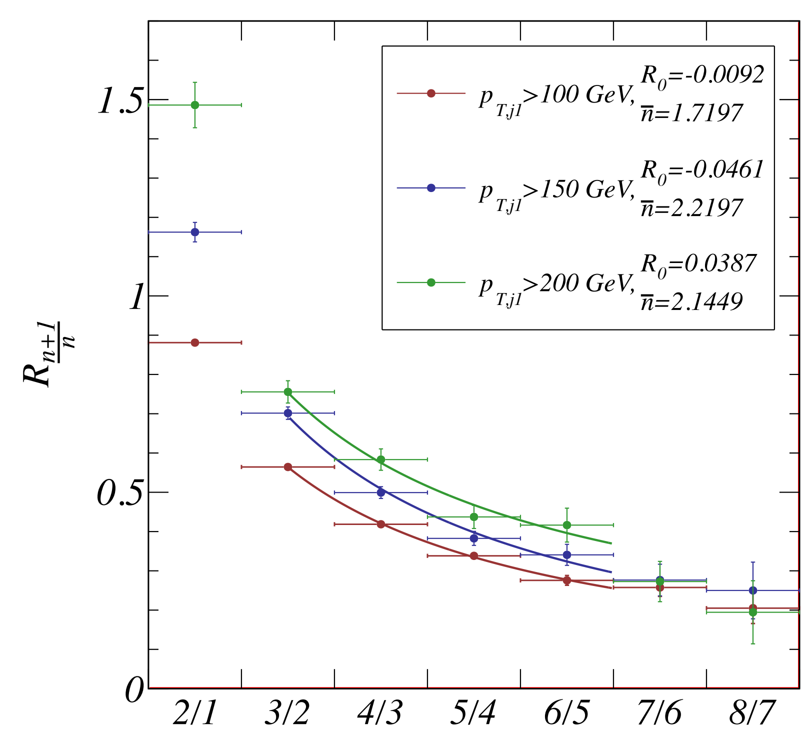


translate to Z plus jets

same hard process (QCD p.o.v.)

but: important background

great laboratory!



[JHEP 1202 (2012) 030]

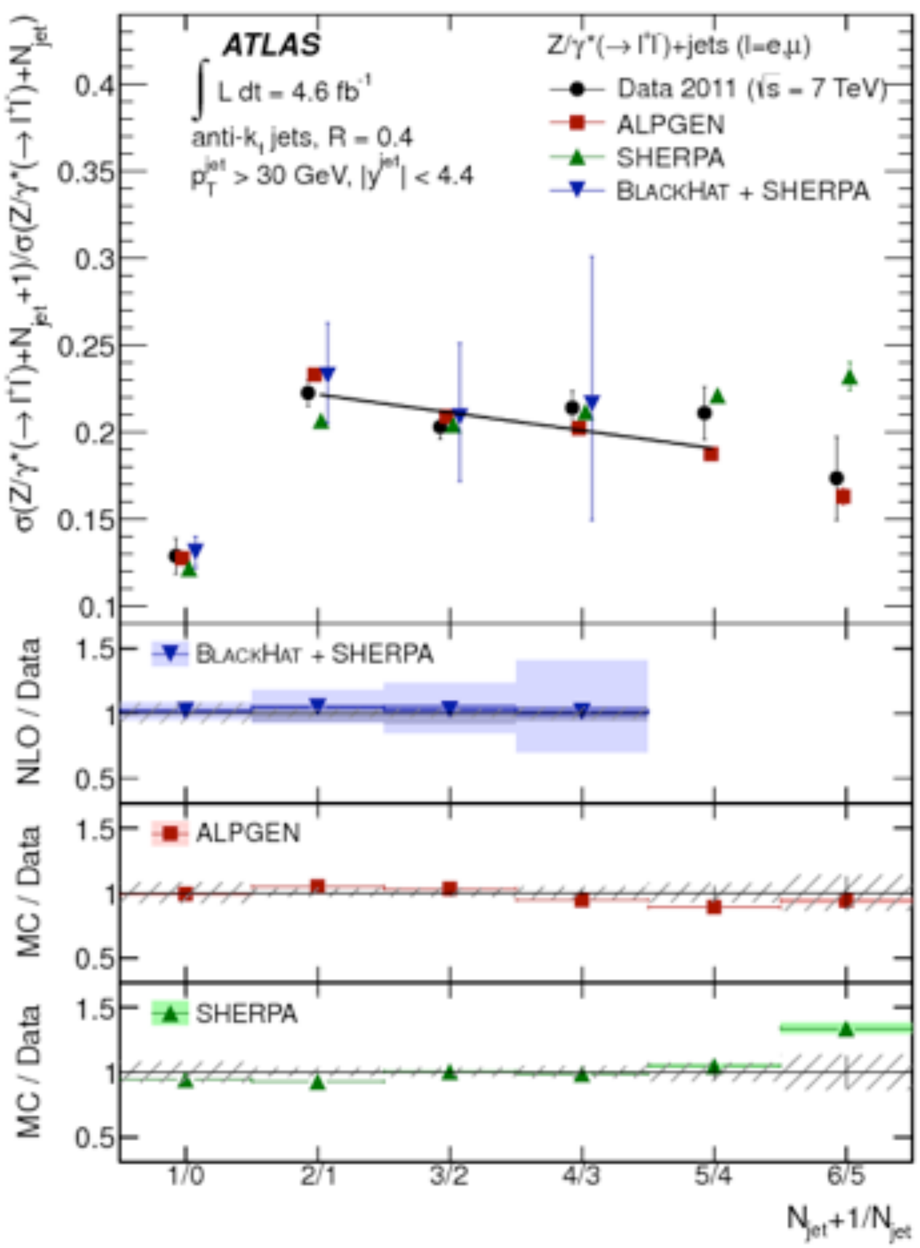
learn, test, ...

actual LHC study

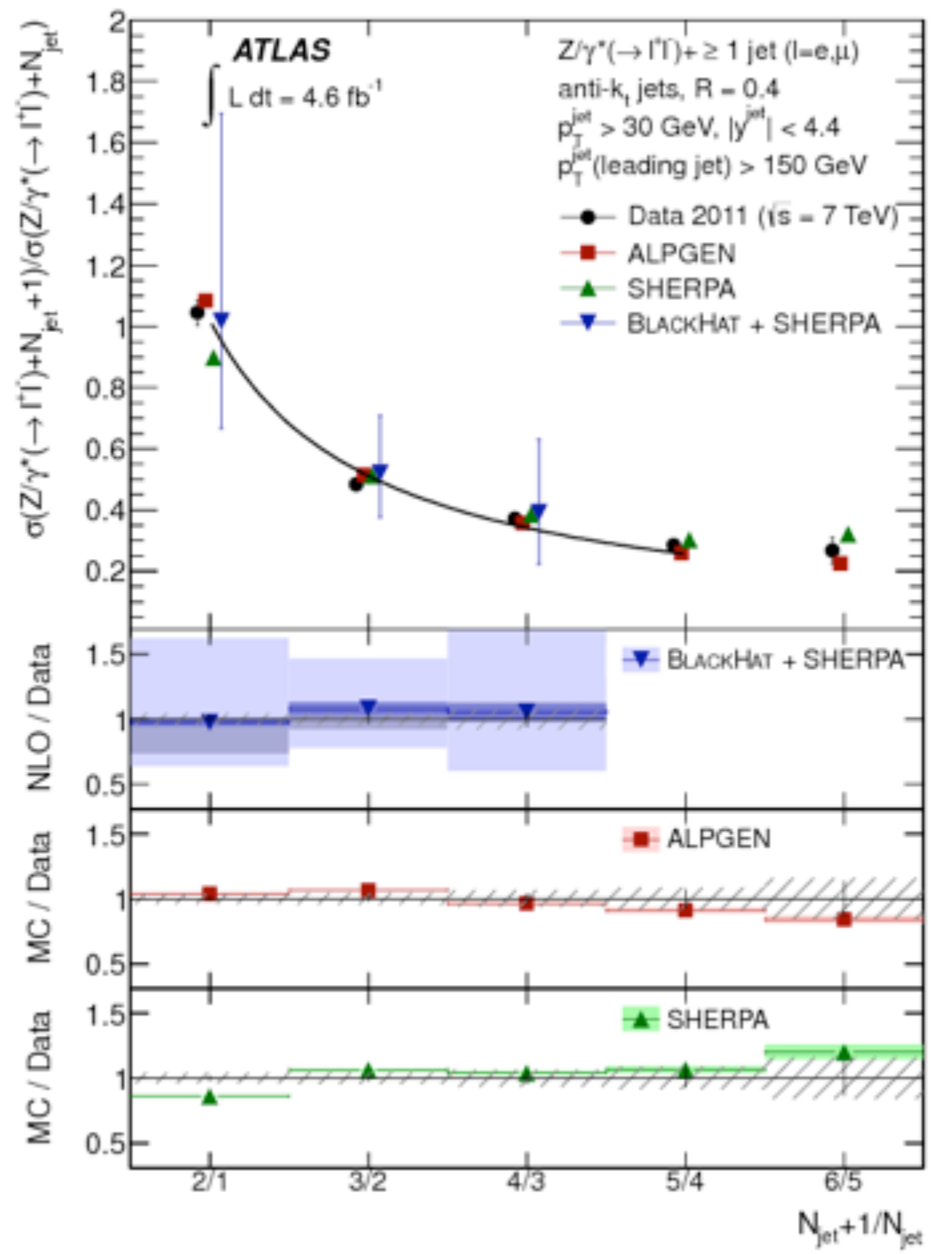
[arXiv:1304.7098]

Z plus jets

[arXiv:1304.7098]

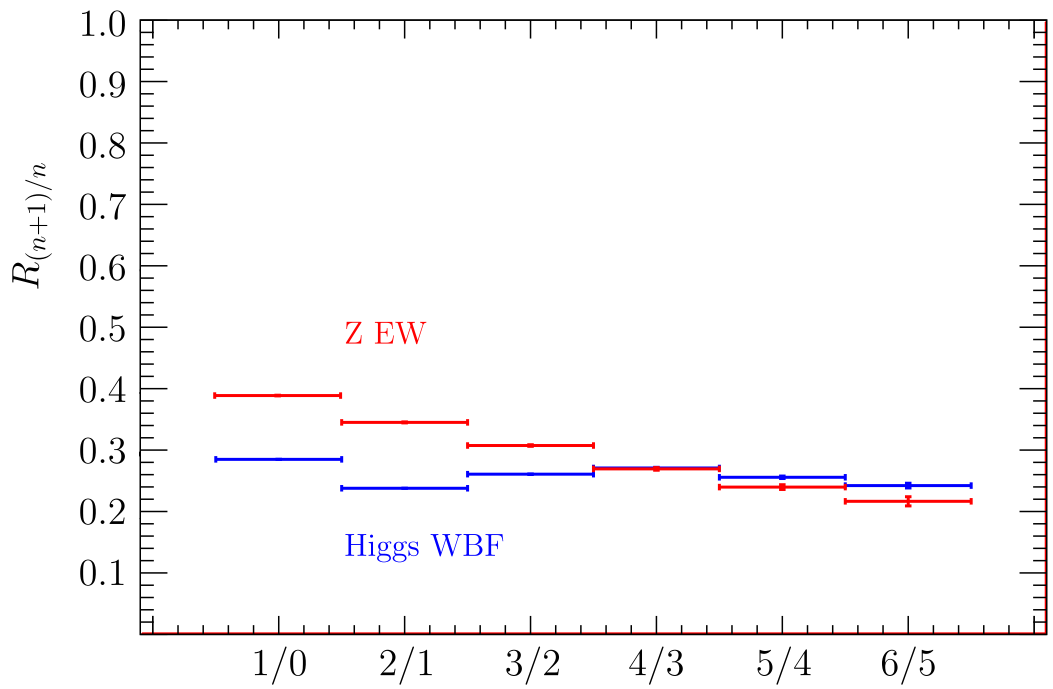


Note:
→ staircase has tilt
→ Poisson flattens out
→ exactly as predicted
→ NLO stops at 4 jets



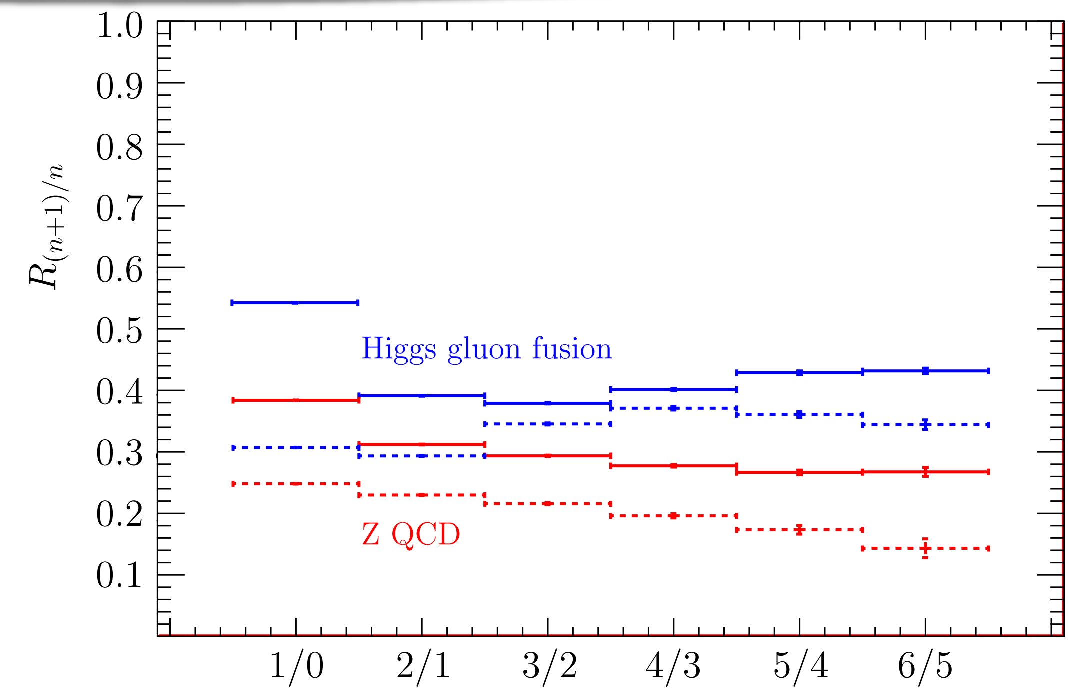
Higgs vetos

… and use!



before cuts

both staircase

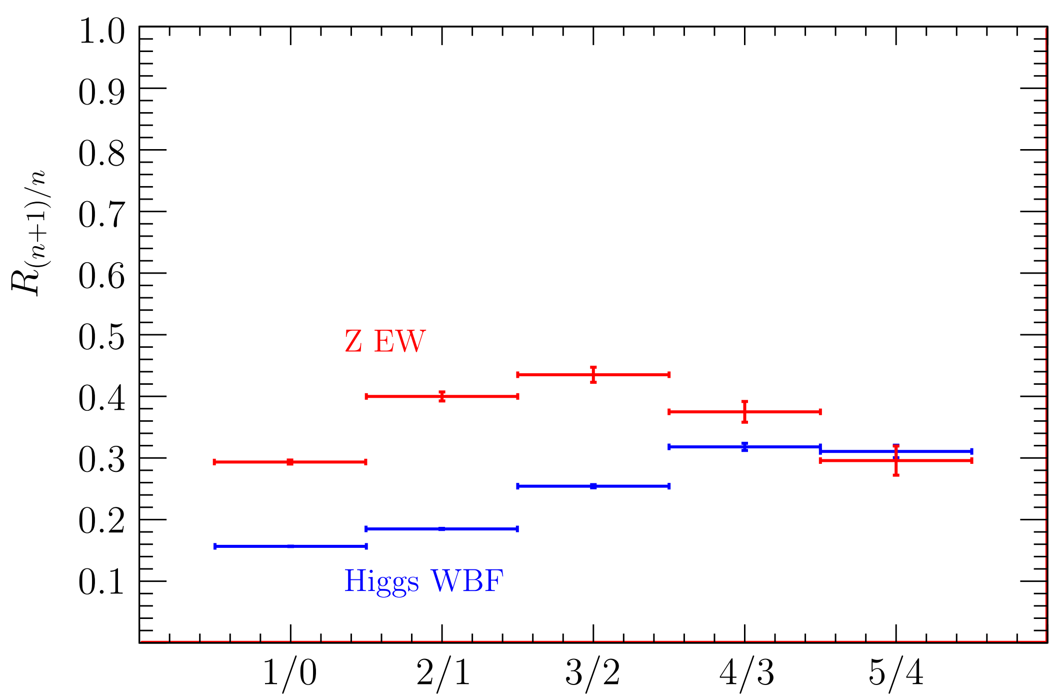


signal stays staircase like

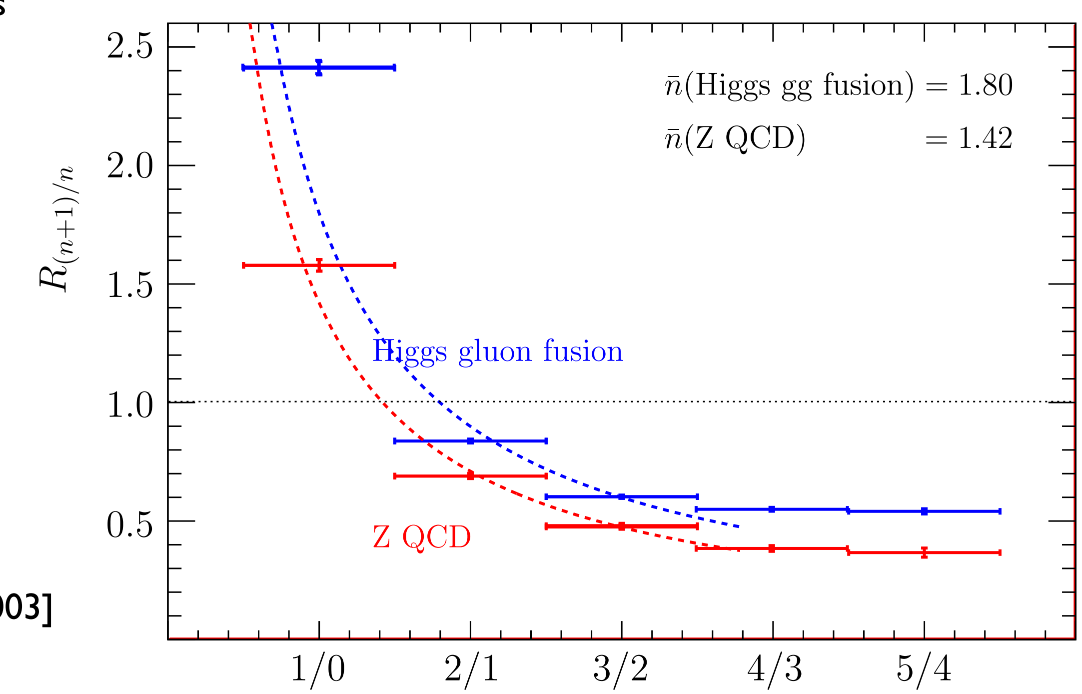
WBF cuts

ask for two hard tagging jets

background becomes Poisson



[Phys.Rev.Lett. 108 (2012) 032003]



LHC gap studies

(extending an existing study)

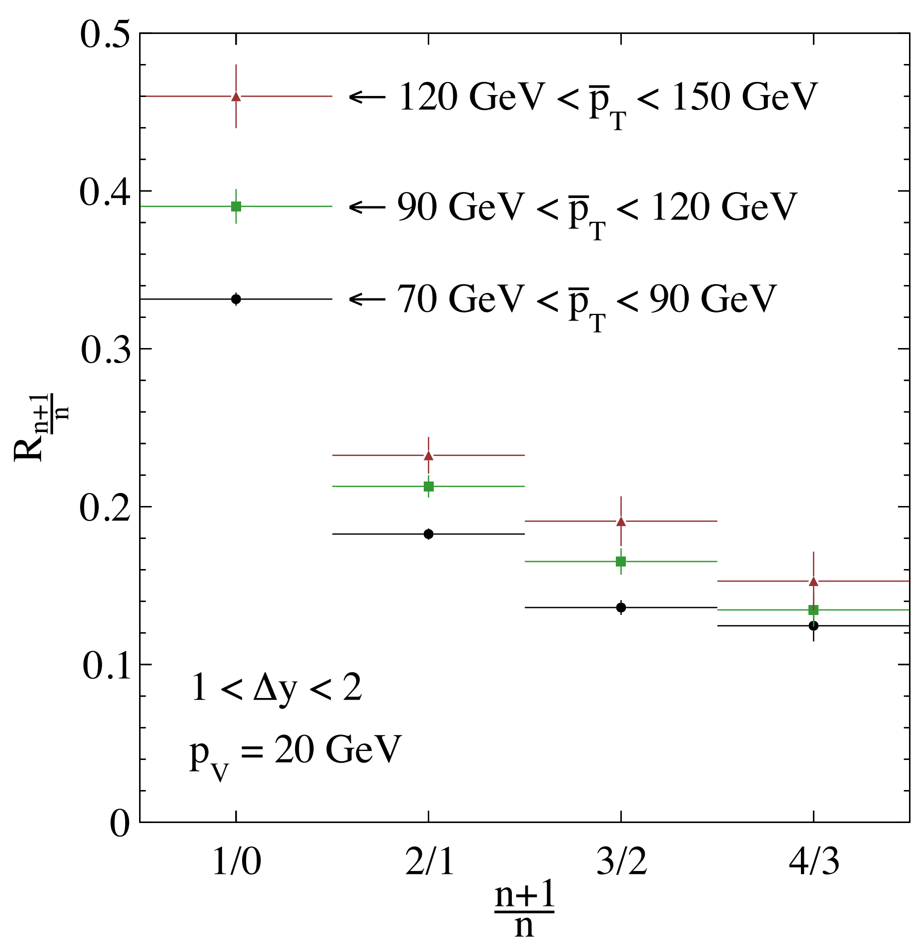
... and use!

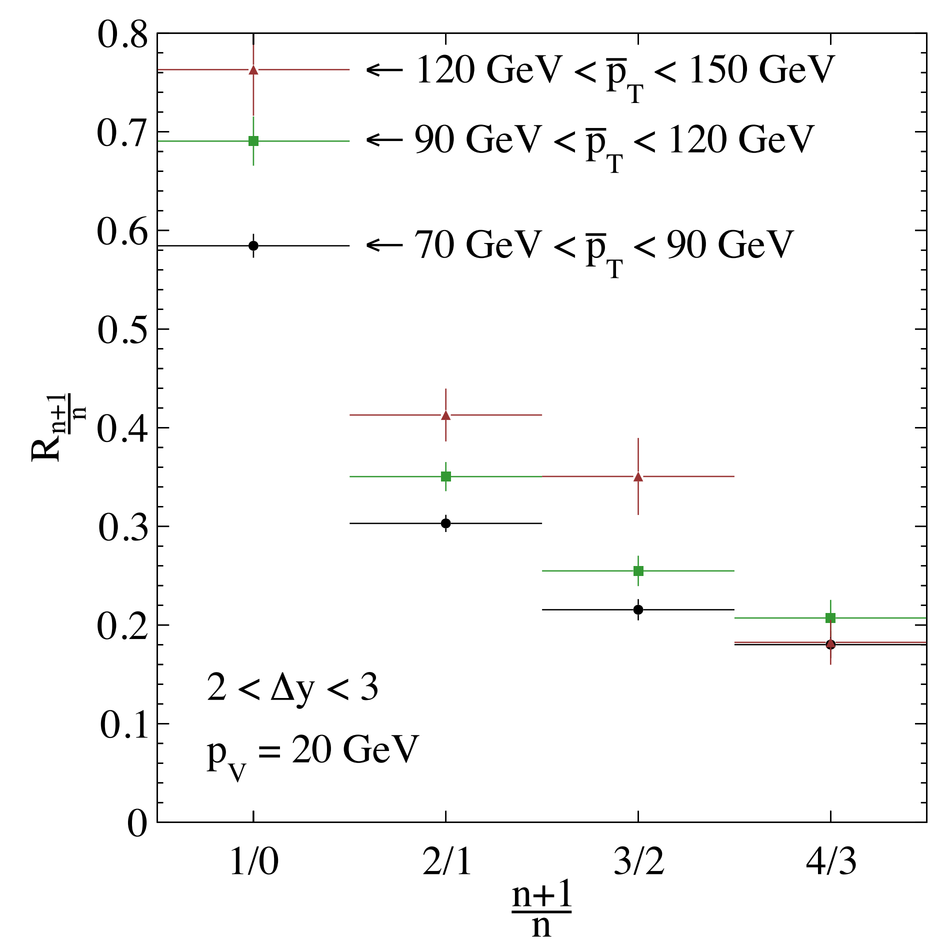
define two hard tagging jets

measure gap fraction $P(0) = \frac{\sigma_0}{\sigma_{\text{tot}}}$

jet veto p_V

in addition: measure jet sprectrum
→ expect Poisson

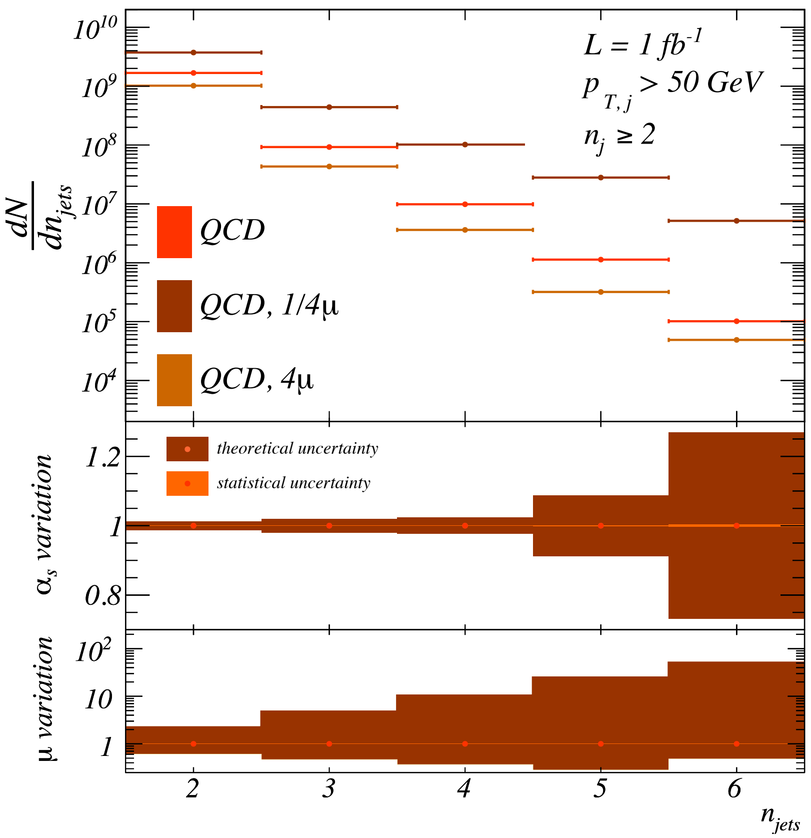


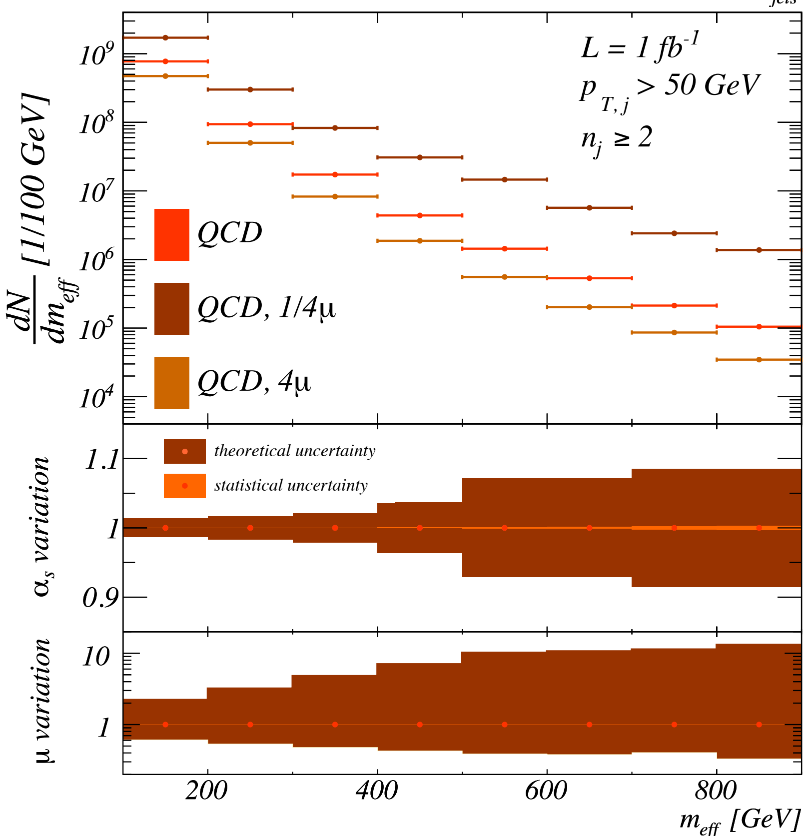


[JHEP 1210 (2012) 162]

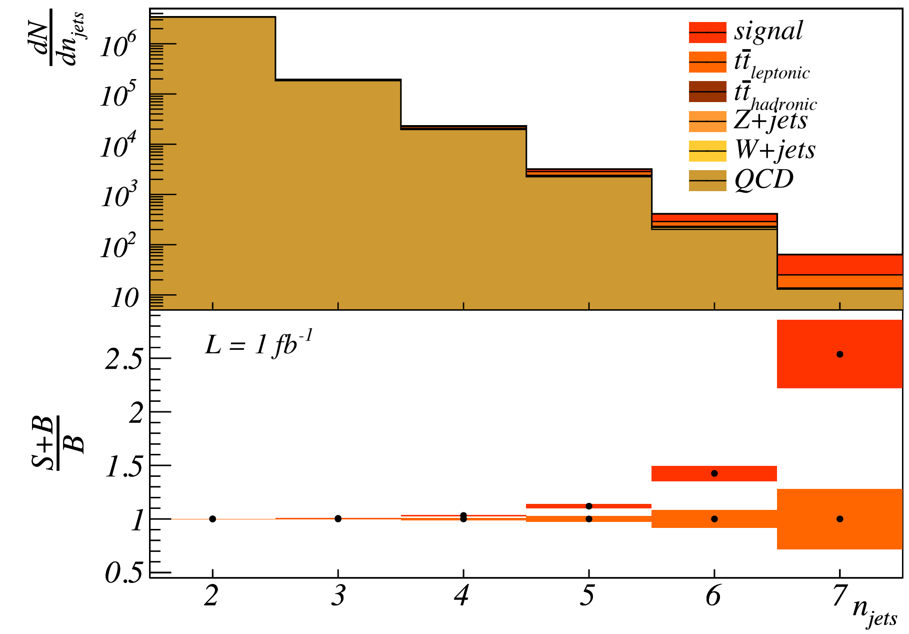
BSM searches with autofocus

... and use!





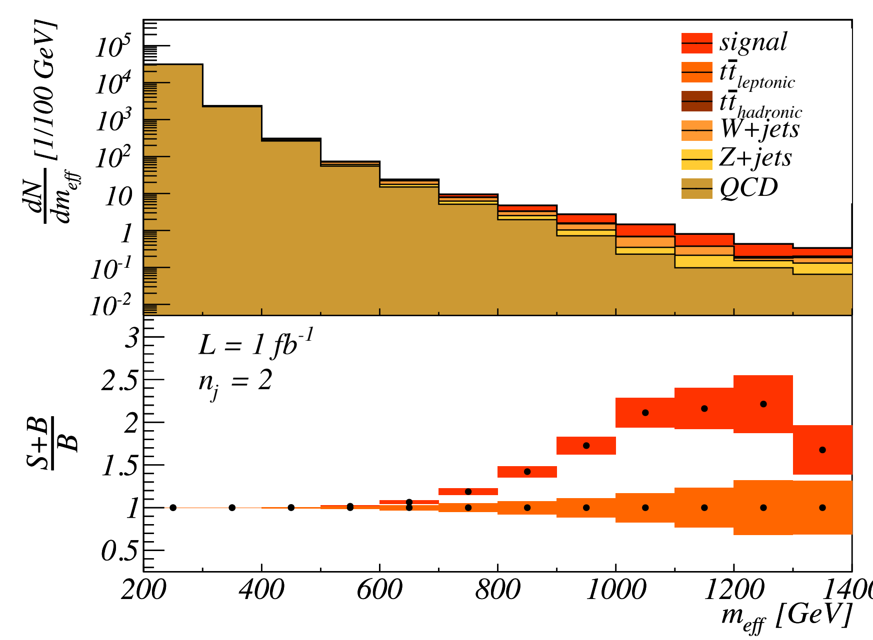
←understand jets
discriminate decay chains →



use notorious observables:

e.g. $$m_{\text{eff}} = \not{p}_T + \sum_{\text{all jets}} p_{T,jet}$$

depends on exclusive number of jets



complementary

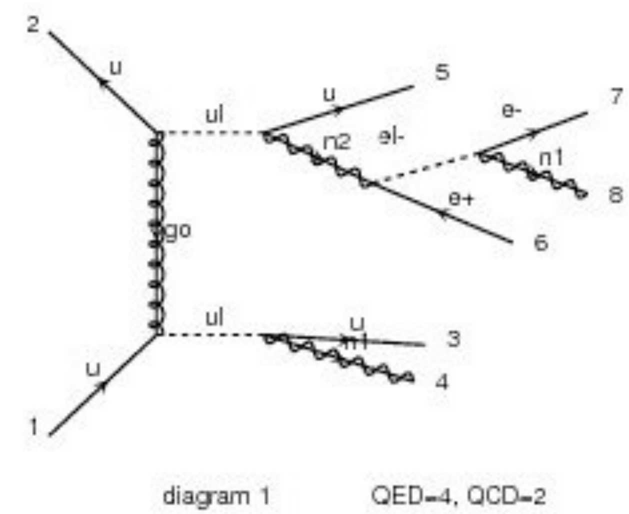
[Phys.Rev. D83 (2011) 095009]

BSM searches with autofocus

... and use!

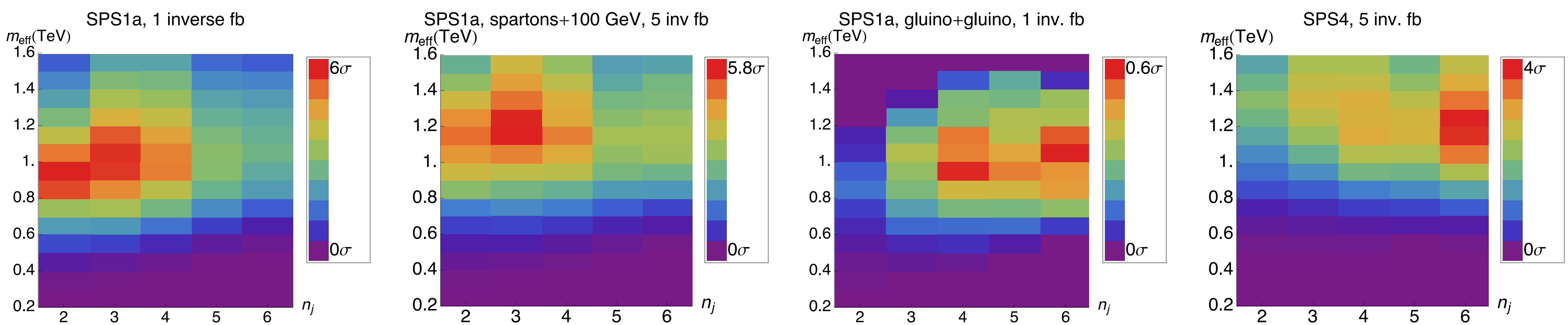
number of jets → color structure
effective mass → particles mass scale

SUSY benchmark points



← decay chains

log-likelihood maps → autofocus



[Phys.Rev. D83 (2011) 095009]

conclusions

→ staircase scaling is a firm QCD prediction
@ LHC: low multiplicities due to PDF effects
→ compute staircase scaling breaking terms [new]
→ staircase and Poisson scaling are an observed fact
→ precession test of QCD at high multiplicity [not possible with NLO]
→ tons of pheno applications:
Higgs studies, photon laboratory, BSM searches, jet substructure(?)

thanks for listening