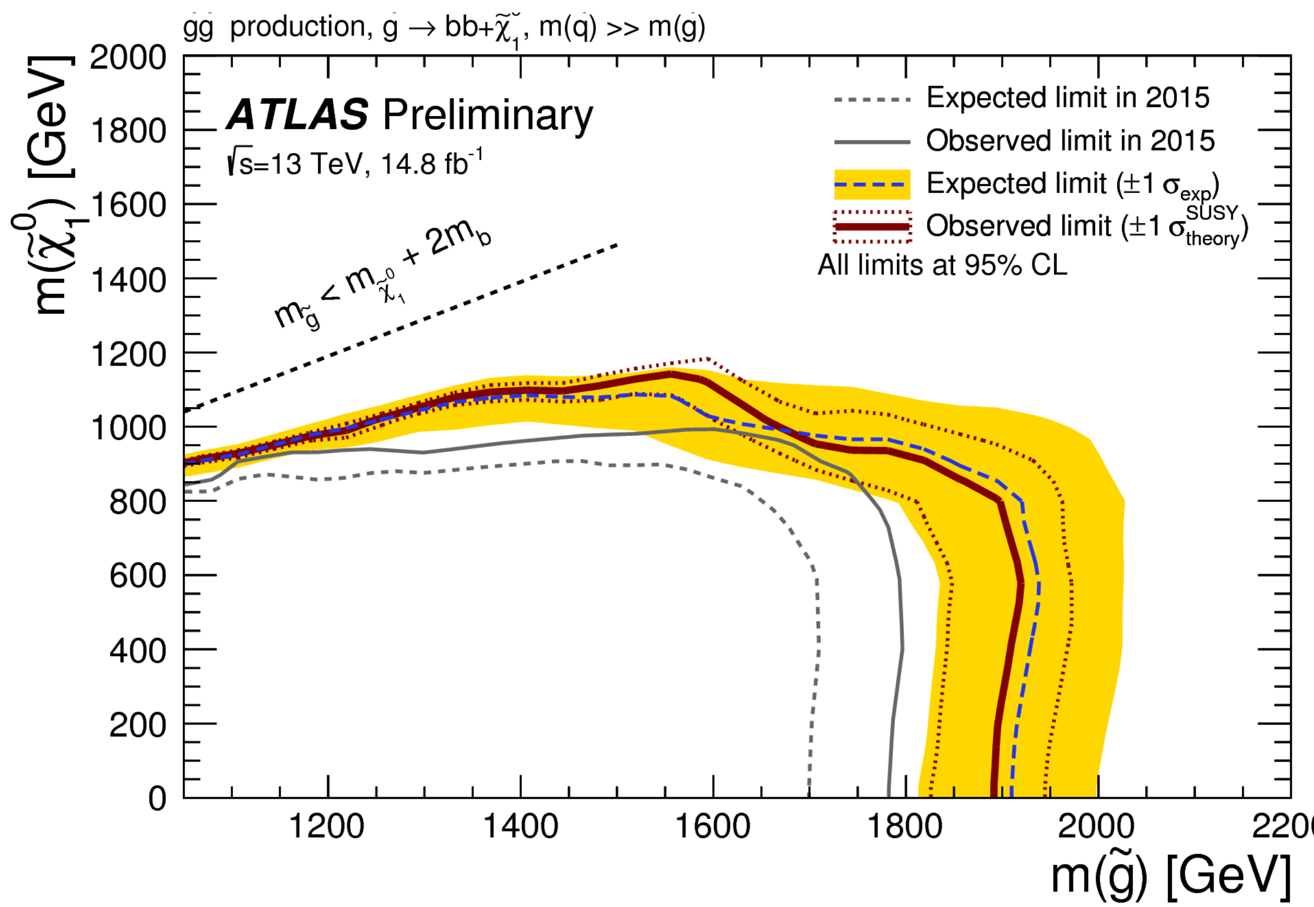
Theoretical summary

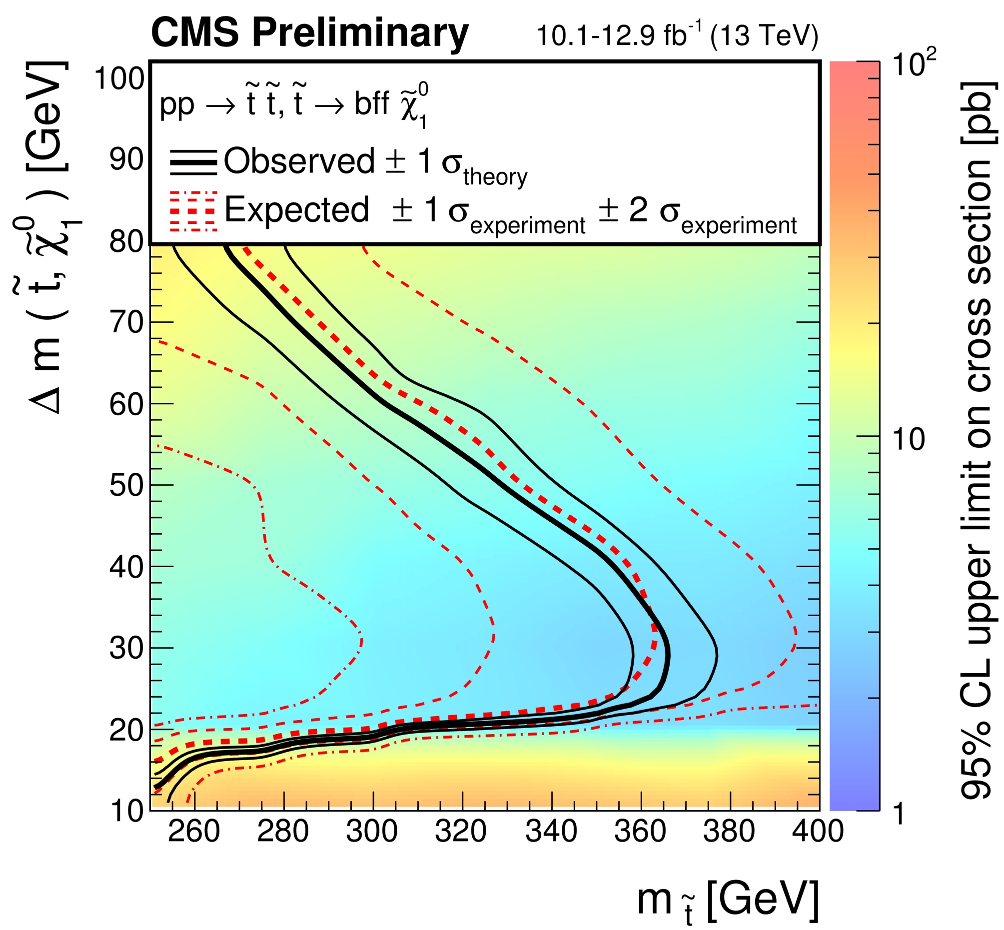
Kirill Melnikov

TTP KIT

QCD@LHC 2016

A repeated theme at this conference is that QCD is everywhere at the LHC.
Well, everywhere is fine but lets hope it is not everything !



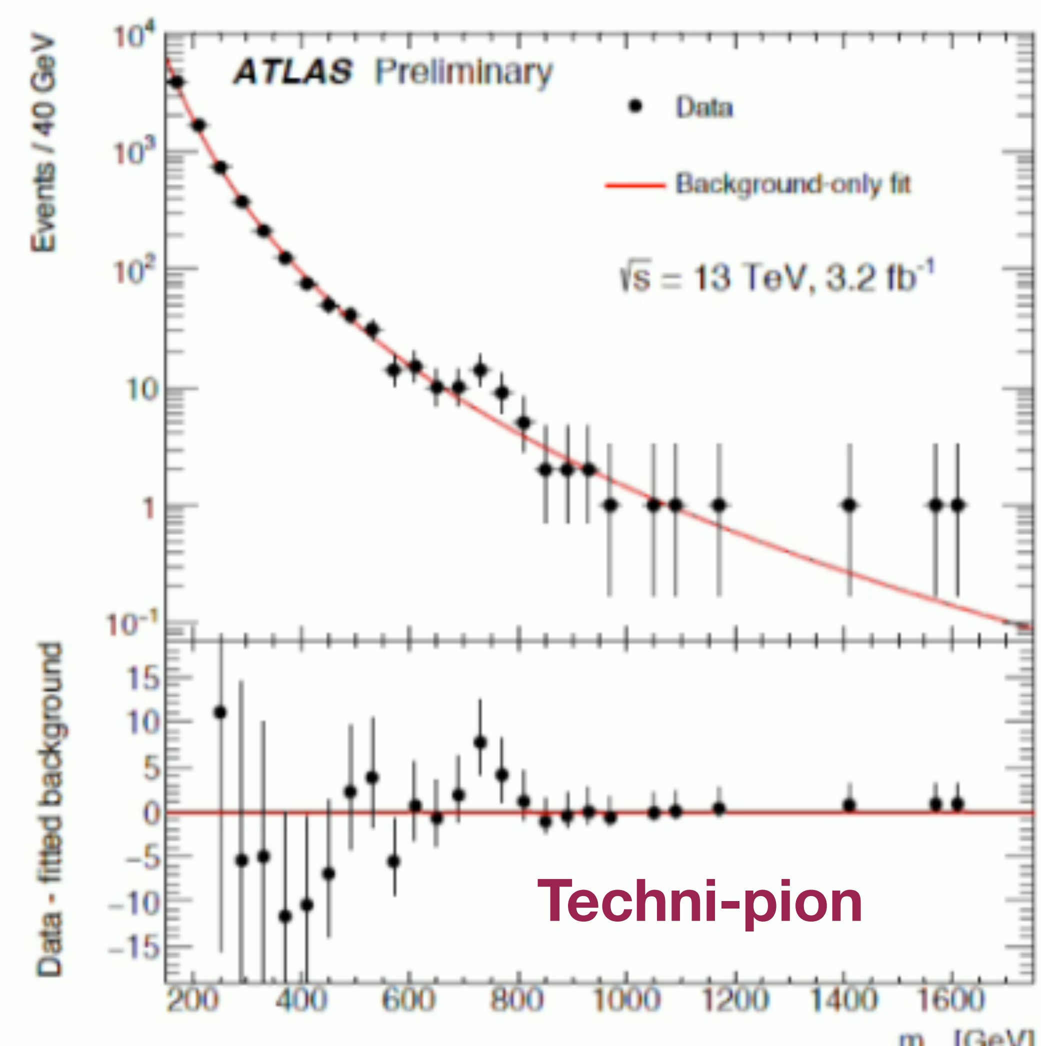


Exclusion limits for stops and gluinos after ICHEP2016

In fact, given the large number of talks on electroweak effects at the LHC, talks on B-physics and CP-violation, any unbiased observer would conclude that the Standard Model is part of a bigger theory called QCD ....

``Huge registrations lines are formed as physicists from all over the world assemble for the annual QCD@LHC conference to discuss the recent discovery of what appears to be an unexpectedly large number of techni-hadrons at the Large Hadron Collider...”

Registration line for the QCD@LHC 202???



QCD is a confining theory with unclear relation to the real world

Yang–Mills and Mass Gap

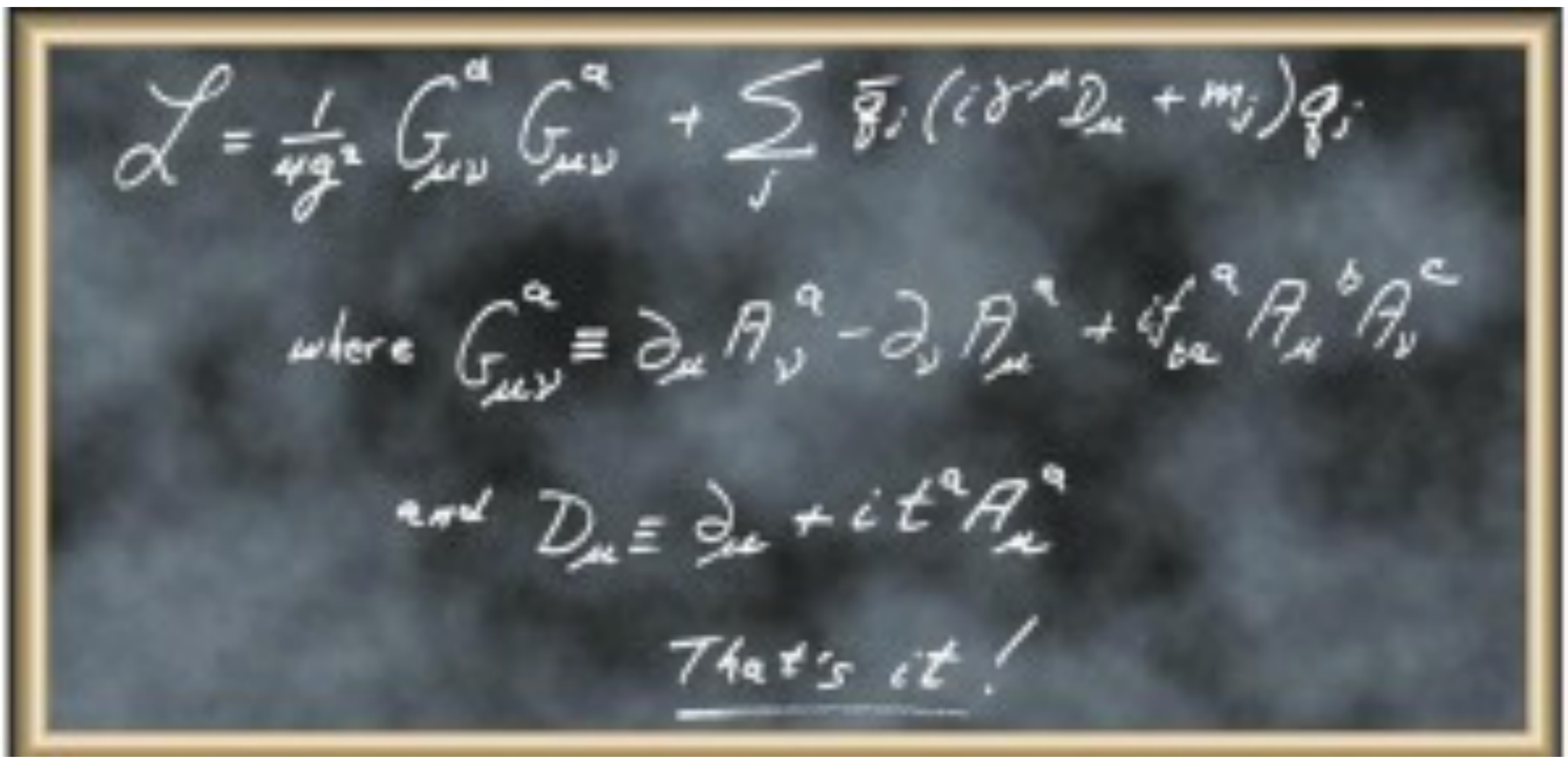
The laws of quantum physics stand to the world of elementary particles in the way that Newton's laws of classical mechanics stand to the macroscopic world. Almost half a century ago, Yang and Mills introduced a remarkable new framework to describe elementary particles using structures that also occur in geometry. Quantum Yang-Mills theory is now the foundation of most of elementary particle theory, and its predictions have been tested at many experimental laboratories, but its mathematical foundation is still unclear. The successful use of Yang-Mills theory to describe the strong interactions of elementary particles depends on a subtle quantum mechanical property called the "mass gap": the quantum particles have positive masses, even though the classical waves travel at the speed of light. This property has been discovered by physicists from experiment and confirmed by computer simulations, but it still has not been understood from a theoretical point of view. Progress in establishing the existence of the Yang-Mills theory and a mass gap will require the introduction of fundamental new ideas both in physics and in mathematics.

This problem is:
Unsolved

Prize money $1000000!

QCD is a confining theory but we are not in this business for the money...

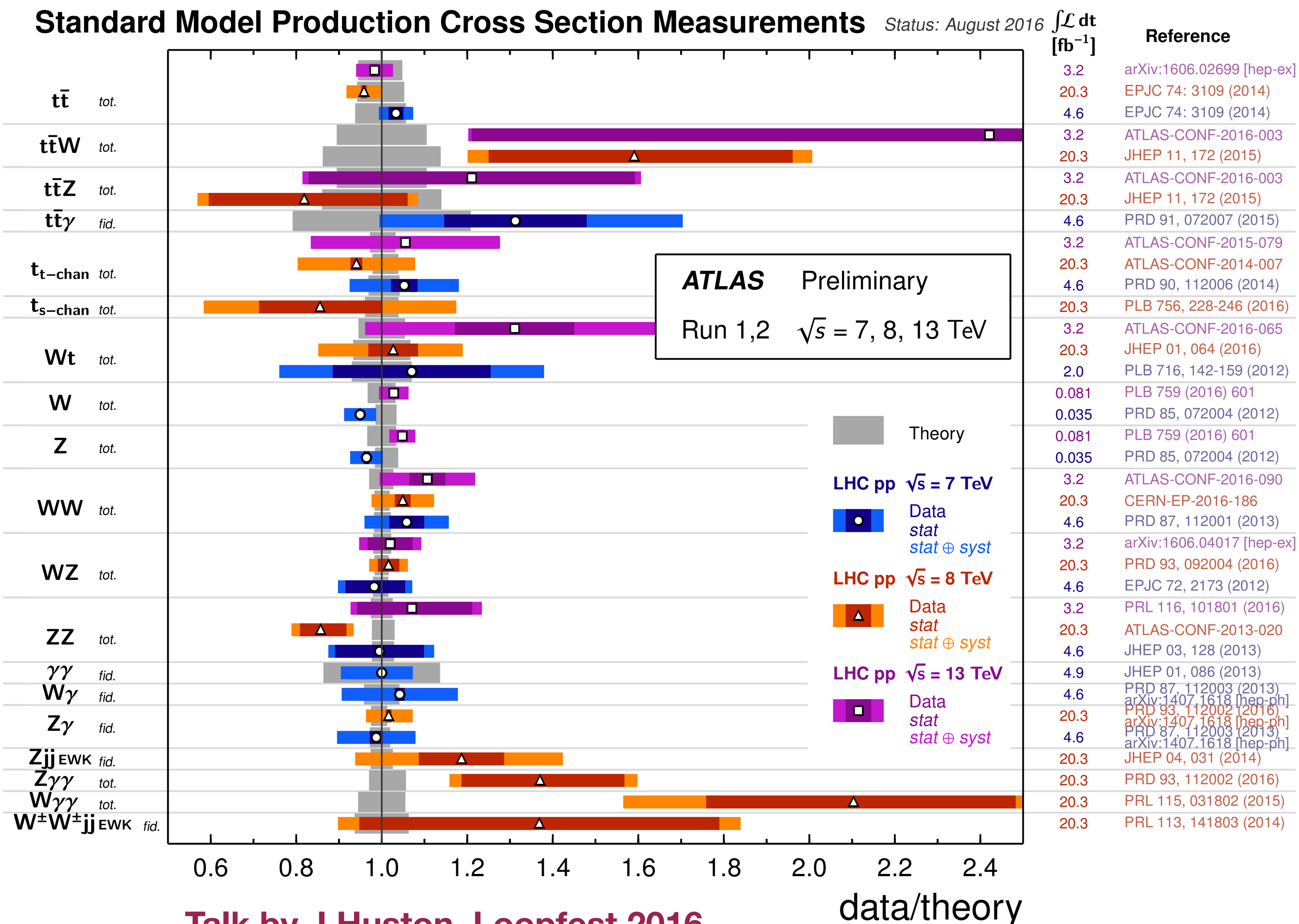
So, we focus on the LHC physics where QCD is ``just” the theory of interacting quarks and gluons with limited non-perturbative contamination.



We then expect that QCD@LHC results are derivable from first principles.

Physics from first principles

This is indeed true as confirmed by a plethora of measurement at the LHC at the unprecedented level of precision.



Talk by J.Huston, Loopfest 2016

The main consequence of the predictivity from first principles is the existence of a systematic improvable perturbative expansion...

The main consequence of predictivity from first principles is the existence of the systematic perturbative expansion...

LO QCD is not a model

NLO QCD is not a model

NNLO QCD is not a model

....

The main consequence of predictivity from first principles is the existence of the systematic perturbative expansion...

LO is not a model
NLO is not a model
NNLO is not a model
....

Pythia is not QCD
Herwig is not QCD
Sherpa is not QCD
Geneva is not QCD

The main consequence of predictivity from first principles is the existence of the systematic perturbative expansion...

LO is not a model

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....

Pythia is not QCD

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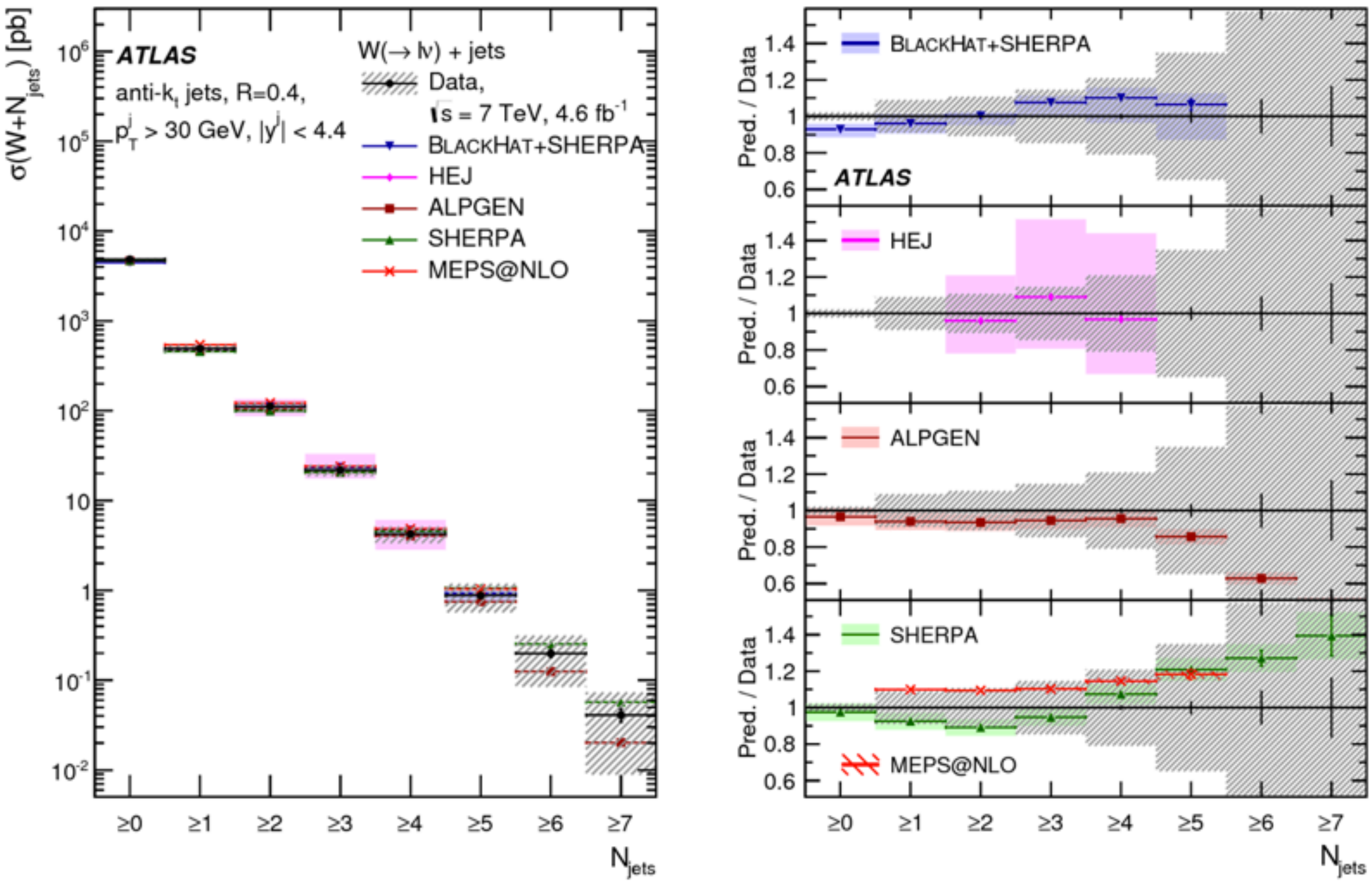
Geneva is not QCD

SCET is not a theory
-- it is a framework !

As the time goes and our understanding of QCD improves, we will probably be able to extend the ``first-principles” aspect of what we do to broader classes of observables and more complicated processes. How successful we eventually will be remains to be seen but the current situation is encouraging.

Complex final states from first principles



Complex final states: how did it all start

It all started with the NLO QCD wishlist that you see below. Note that this was a hell of a wish to have back in circa 2004

Note that we have ticked off one cross section from the first list

An experimenter's wishlist

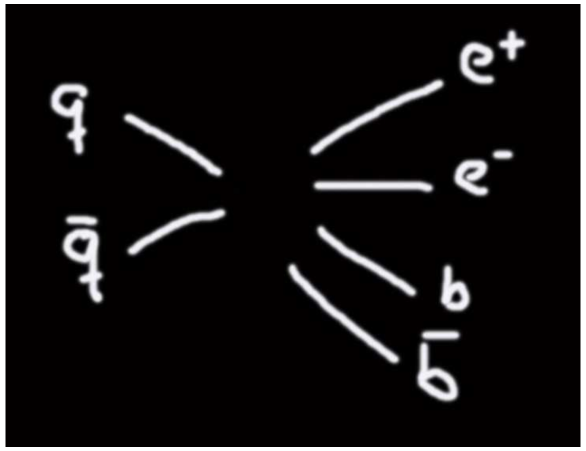
Run II Monte Carlo Workshop

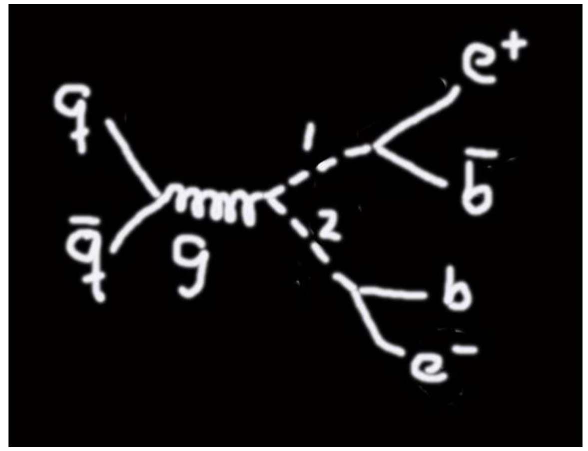
Single Boson	Diboson	Triboson	Heavy Flavour
$W+\leq 5j$	$WW+\leq 5j$	$WWW+\leq 3j$	$t\bar{t}+\leq 3j$
$W+b\bar{b}\leq 3j$	$W+b\bar{b}+\leq 3j$	$WWW+b\bar{b}+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}\leq 3j$	$W+c\bar{c}+\leq 3j$	$WWW+\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 5j$	$ZZ+\leq 5j$	$Z\gamma\gamma+\leq 3j$	$t\bar{t}+Z+\leq 2j$
$Z+b\bar{b}+\leq 3j$	$Z+b\bar{b}+\leq 3j$	$ZZZ+\leq 3j$	$t\bar{t}+H+\leq 2j$
$Z+c\bar{c}+\leq 3j$	$ZZ+c\bar{c}+\leq 3j$	$WZZ+\leq 3j$	$t\bar{b}\leq 2j$
$\gamma+\leq 5j$	$\gamma\gamma+\leq 5j$	$ZZZ+\leq 3j$	$b\bar{b}+\leq 3j$
$\gamma+b\bar{b}\leq 3j$	$\gamma\gamma+b\bar{b}\leq 3j$		...
$\gamma+c\bar{c}\leq 3j$	$\gamma\gamma+c\bar{c}\leq 3j$		
	$WZ+\leq 5j$		
	$WZ+b\bar{b}\leq 3j$		
	$WZ+c\bar{c}\leq 3j$		
	$W\gamma+\leq 3j$		
	$Z\gamma+\leq 3j$		

But who was this experimenter and why did he have a wish like that?

Complex final states

Bard: Interpreting New Frontier Energy Collider Physics

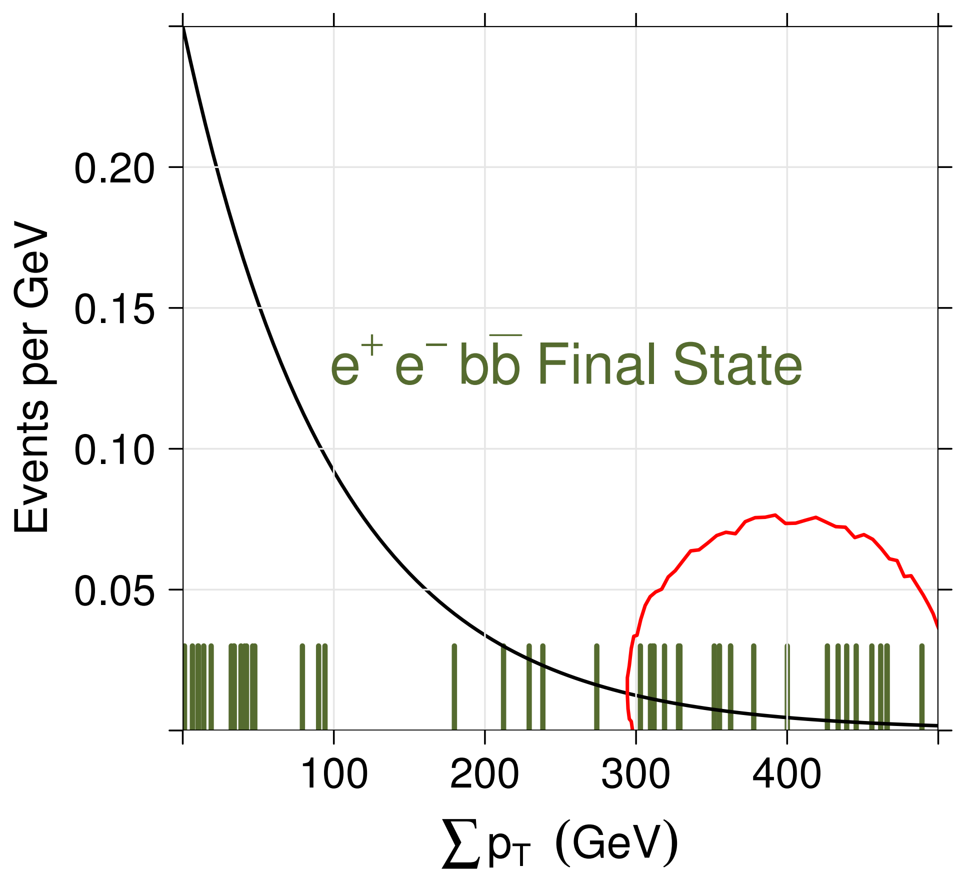




Bruce Knuteson*
MIT

Stephen Mrenna†
FNAL

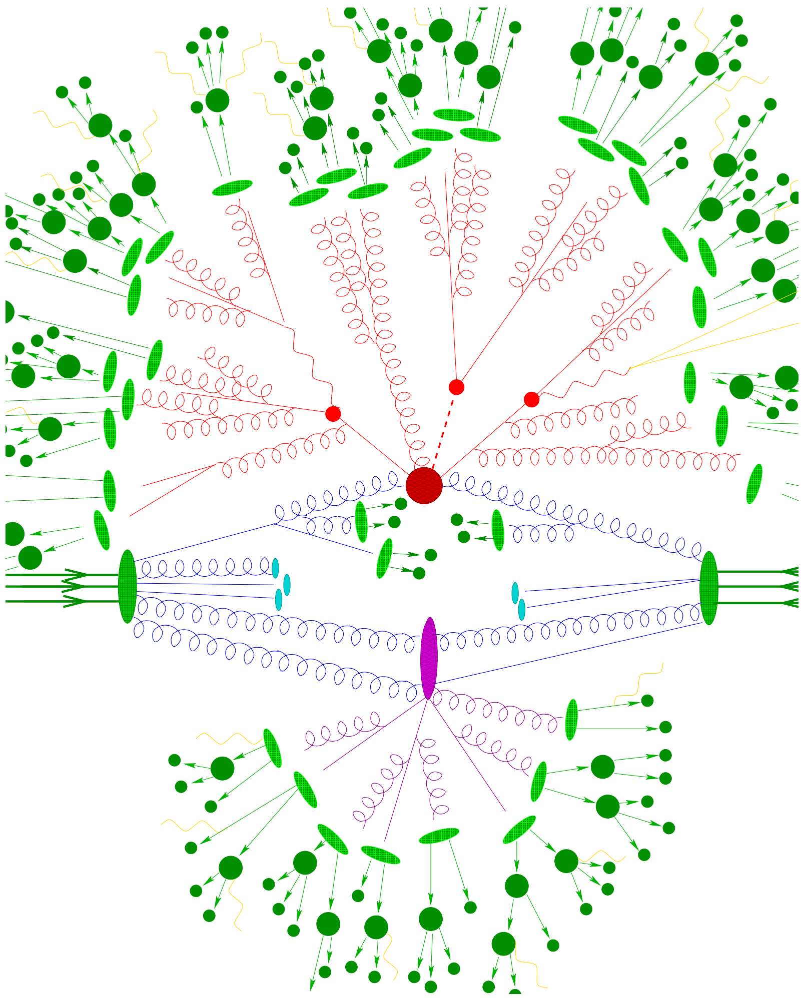
In contemporary high energy physics experiments, it is not uncommon to observe discrepancies between data and Standard Model predictions. Most of these discrepancies have been explained away over time. To convincingly demonstrate that an observed effect is evidence of physics beyond the Standard Model, it is necessary to prove it is (1) not a likely statistical fluctuation, (2) not introduced by an imperfect understanding of the experimental apparatus, (3) not due to an inadequacy of the implementation of the Standard Model prediction, and (4) interpretable in terms of a sensible underlying theory. Those who object to (4) as being necessary fail to appreciate that most hypothesis development in science occurs before, rather than after, publication. This last criterion is essential, and will likely point the way to other discrepancies that must exist if the interpretation is correct.

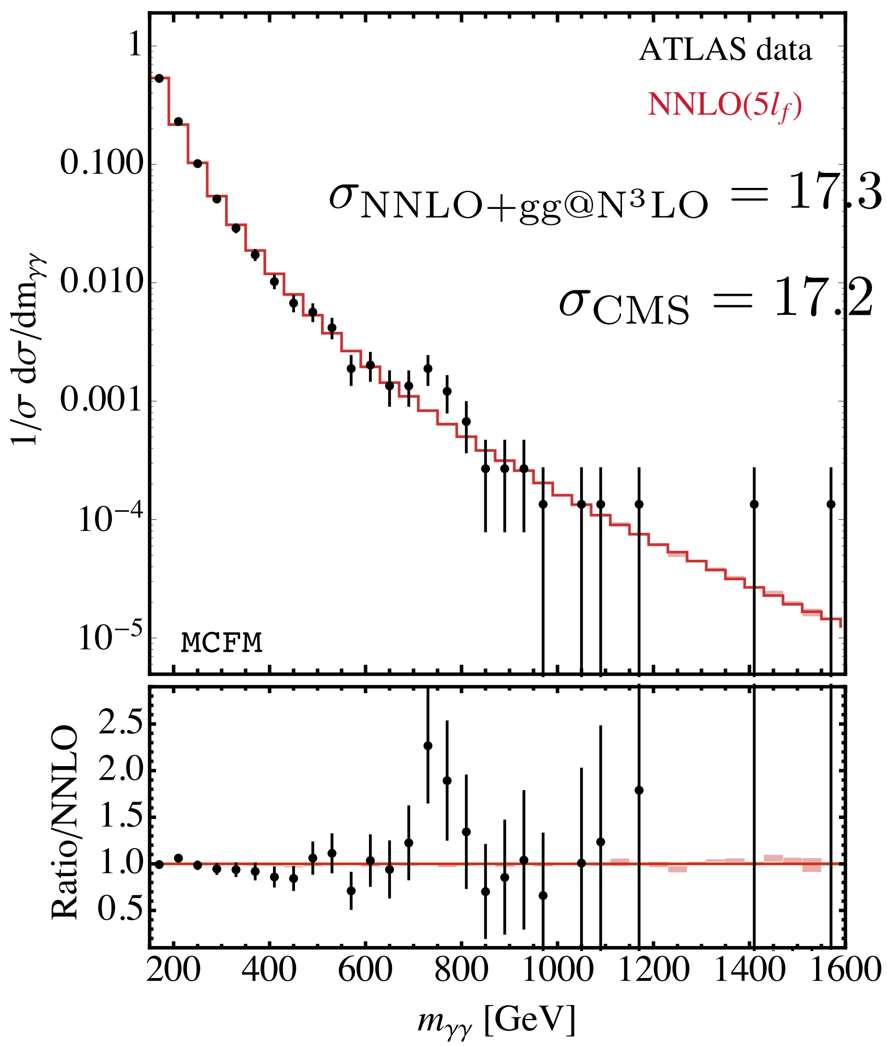


Main goal of the ``experimenter" was to search systematically for a correlated set of deviations from the SM predictions and a possibility to explain them with a single NP hypothesis. With null search results from the LHC, this idea becomes very very timely...

Complex final states

However, it was realized early on that the validity of this idea rests on the assumption that solid theoretical description of complex final states can be provided. This started the NLO arms race...(BLACKHAT, MG@NLO, OpenLoops, GoSam, Samurai....)





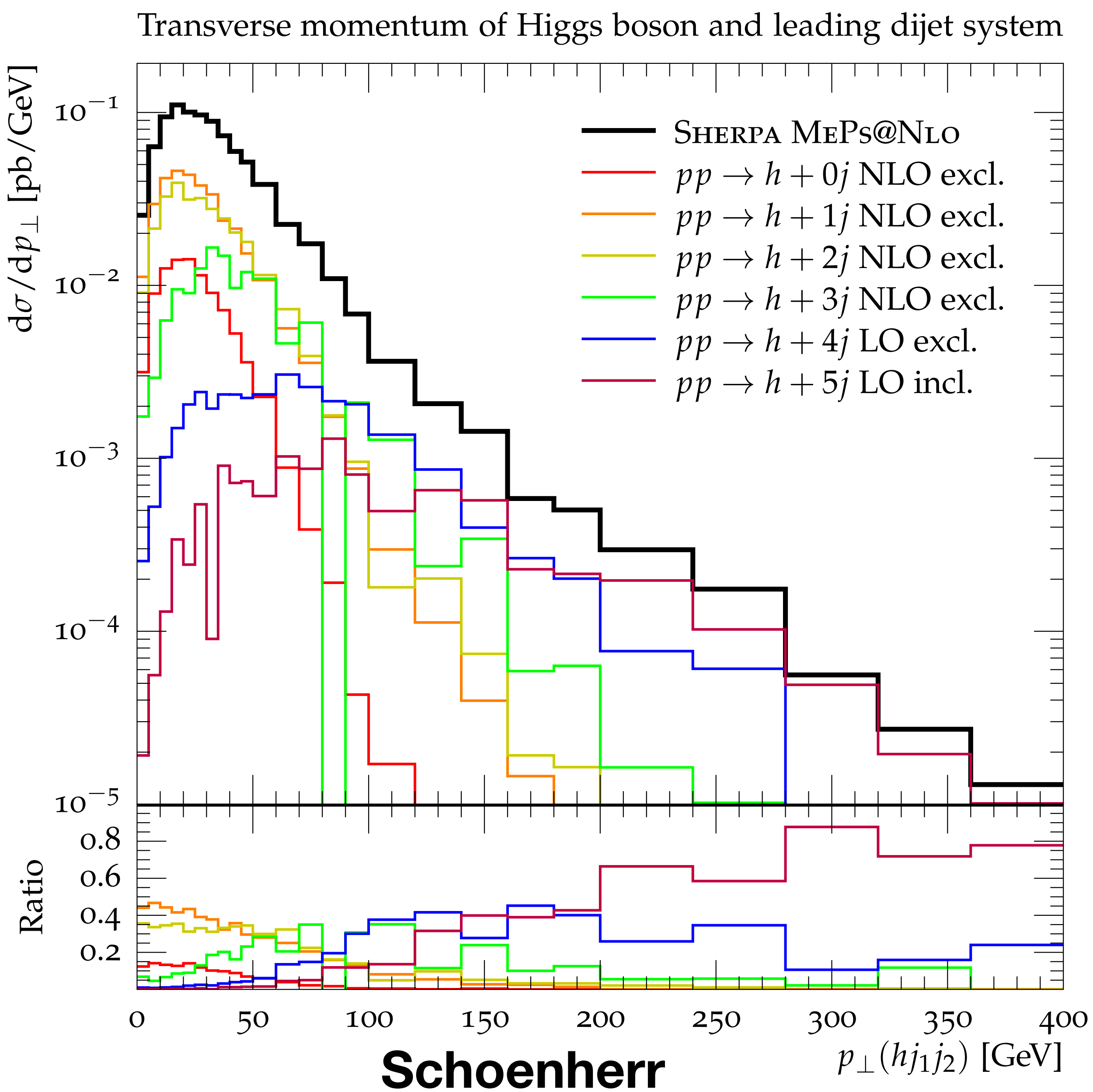
Campbell, Ellis, Li, Williams

Complex final states

NLO QCD + EW calculations can now be performed for very complex processes. To be used as advanced simulation tools, they need to work in accord with parton showers, a phenomenon usually referred to as matching and merging.

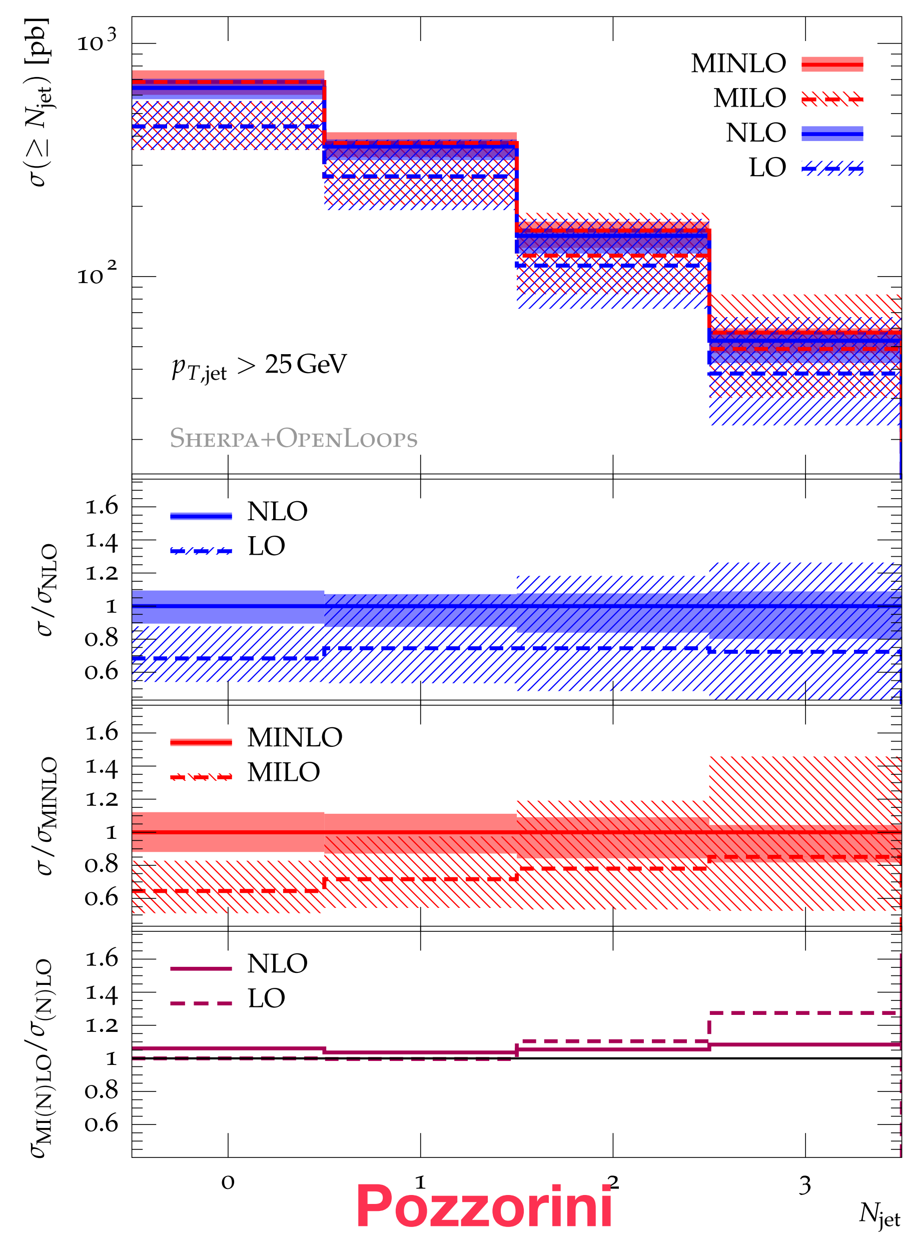
Talks by Pellen, Frederix, Pozzorini, Salfelder, Schoenherr, Uccirati

H+j @ NLO QCD



Schoenherr

tt+3j @ NLO QCD



Pozzorini

Complex final states

Ever matched ? Ever merged? Ever failed?
No matter. Try again. Fail again. Fail Better!

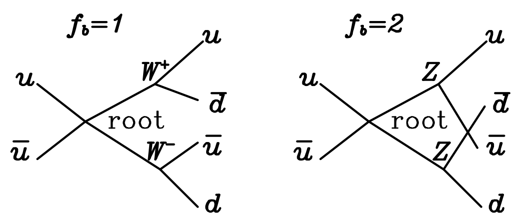
CKKW, MLM, LoPs, NLoPS, NNLOPs, MEPs, MENloPS, MePs@NLO, MC@NLO, POWHEG, MINLO, UNLOPS, FxFx, KirkNLO, etc.

Complex final states: better matching and merging

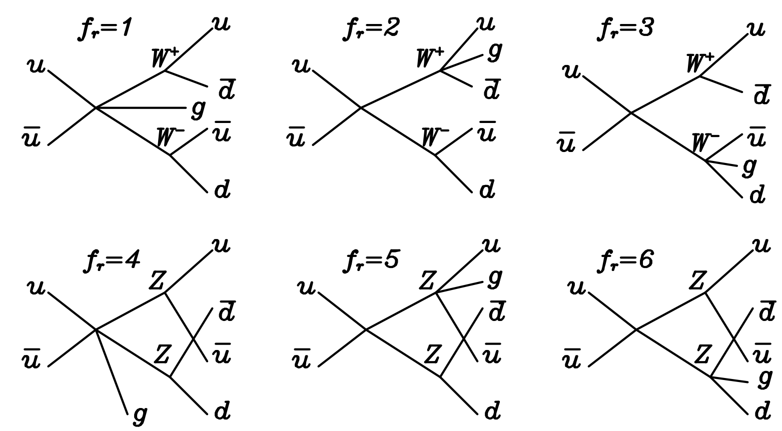
Talks by Torrielli, Lindert, Siodmok, Hamilton

Resonance-aware parton showers and matching solves the problem of inefficient phase-space profiling in the presence of narrow resonances. The idea is to introduce different histories, whose weights are determined by their contributions to inclusive cross sections and then properly generate the kinematics for each of the histories.

LO



NLO



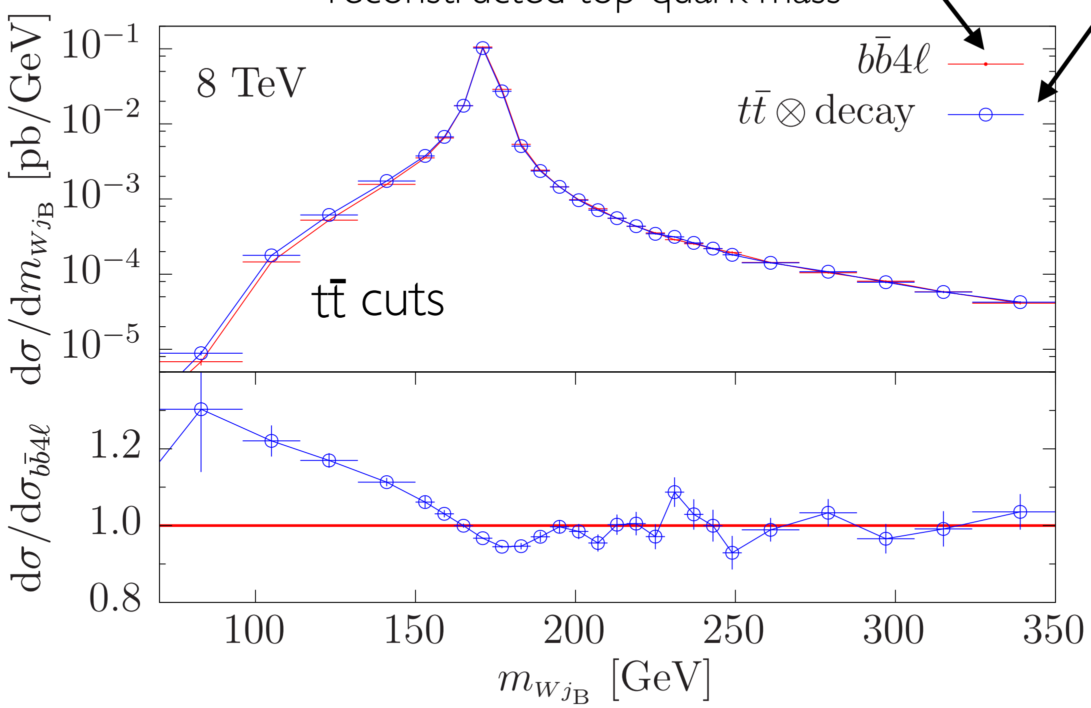
Physics features:

- exact **non-resonant** / **off-shell** / **interference** / **spin-correlation** effects at NLO
- unified treatment of **top-pair and Wt** production with interference at NLO
- access to phase-space regions with **unresolved b-quarks** and/or jet vetoes
- consistent NLO+PS treatment of top resonances, including quantum corrections to top propagators and off-shell top-decay chains

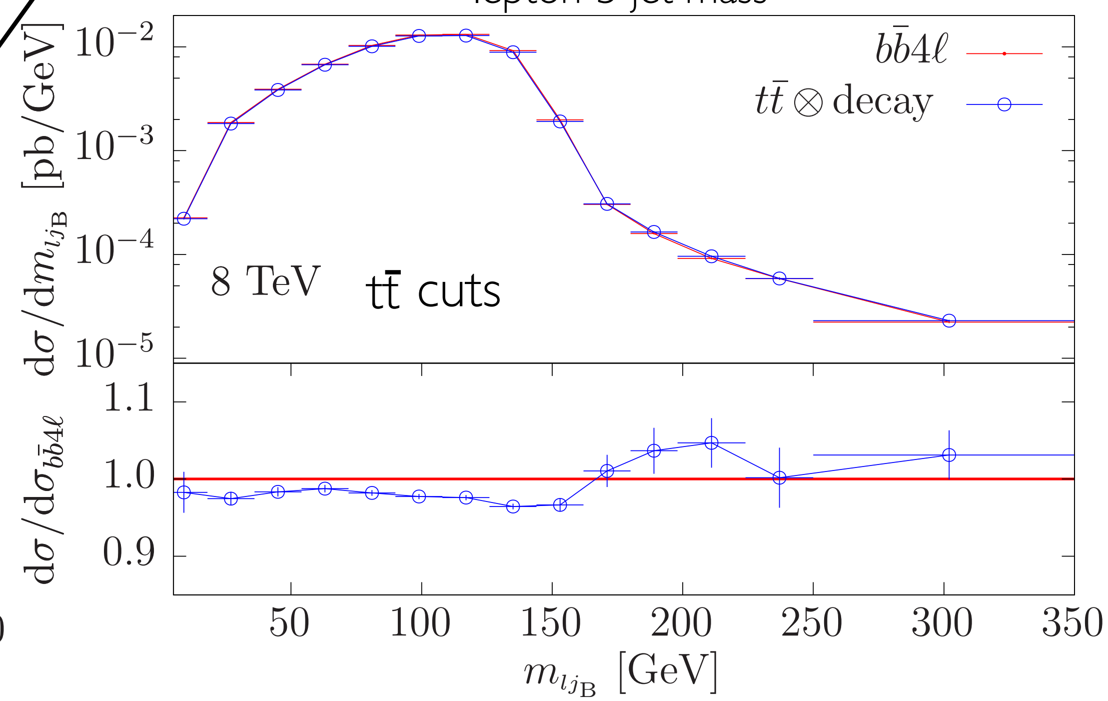
J.Lindert

Complex final states

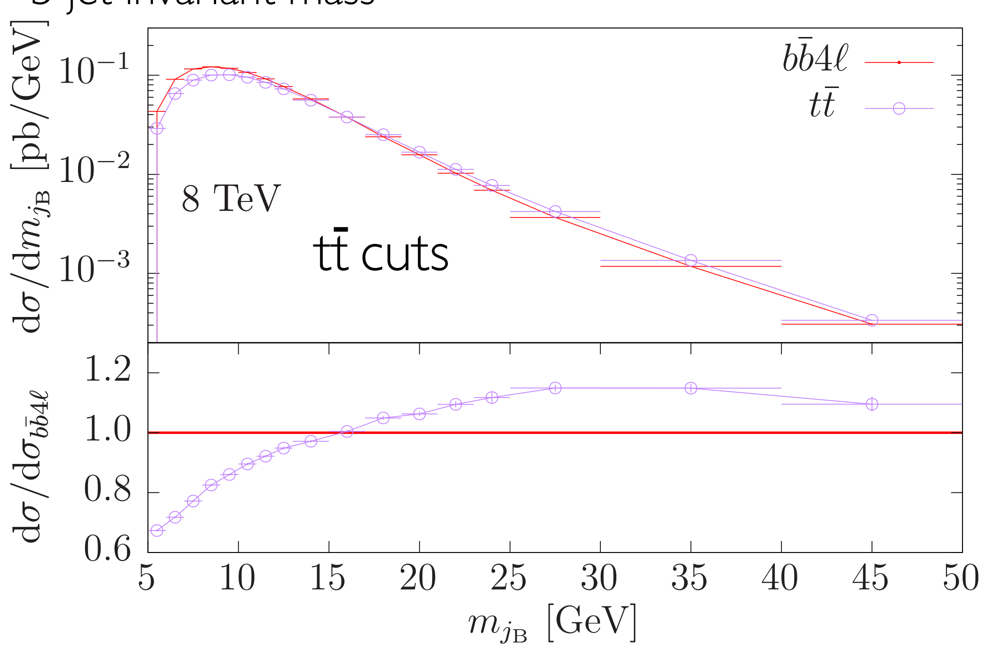
reconstructed top-quark mass



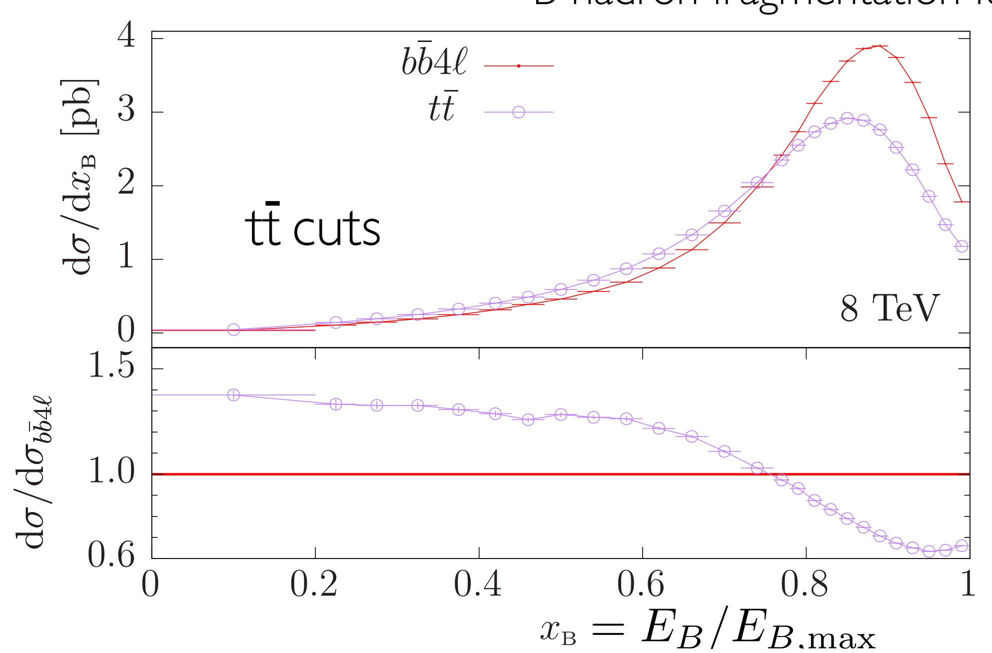
lepton-b-jet mass



b-jet invariant mass



B-hadron fragmentation fu



I don't see why the width/mass suppression does not work in those cases when top quark selection cuts are used. It would be useful to provide parametric arguments that explain why the NWA does not work....

Complex final states: better showers

To better describe complex final states one needs better parton showers -- the goal of Deductor, Dire, Vincia, Geneva. But what is a "better parton shower" at the first place? How can one decide what is "better" without a solid starting point?

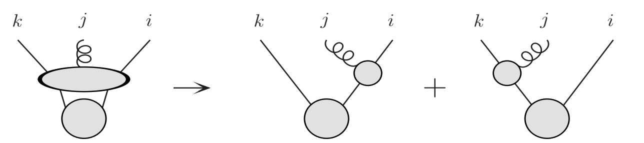
Talks by Prestel, Nagy, Bauer,Siodmok , Fisher, Smilie, Schoenherr

Parton showers – DIRE

Höche, Prestel EPJC75(2015)461

- combination of parton and dipole shower picture
  $\rightarrow$ partial fractioning soft eikonal   Catani,Seymour Nucl.Phys.B485(1997)291

$$\frac{p_i p_k}{(p_i p_j)(p_j p_k)} \rightarrow \frac{1}{p_i p_j}\frac{p_i p_k}{(p_i+p_k)p_j} + \frac{1}{p_k p_j}\frac{p_i p_k}{(p_i+p_k)p_j}$$



- capture dominant coherence effects (3-parton correlations)

$$\frac{1}{1-z} \rightarrow \frac{1-z}{(1-z)^2+\kappa^2} \qquad \kappa^2 = \frac{k_\perp^2}{Q^2}$$

- preserve collinear anomalous dimensions & sum rules
  $\rightarrow$ splitting functions fixed

$$P_{qq}(z,\kappa^2) = 2\,C_F\left[\left(\frac{1-z}{(1-z)^2+\kappa^2}\right)_+ - \frac{1+z}{2}\right] + \gamma_q\,\delta(1-z)$$

$$P_{gg}(z,\kappa^2) = 2\,C_A\left[\left(\frac{1-z}{(1-z)^2+\kappa^2}\right)_+ + \frac{z}{z^2+\kappa^2} - 2 + z(1-z)\right] + \gamma_g\,\delta(1-z)$$

$$P_{qg}(z,\kappa^2) = 2\,C_F\left[\frac{z}{z^2+\kappa^2} - \frac{2-z}{2}\right] \qquad P_{gq}(z,\kappa^2) = T_R\left[z^2+(1-z)^2\right]$$

Evolution equation

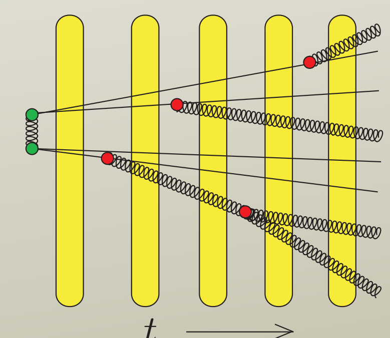
$$|\rho(t)) = \mathcal{U}_\mathcal{S}(t,t_0)|\rho(t_0)) \qquad \mathcal{H}_I(t) = \text{splitting operator}$$

$$\frac{d}{dt}\mathcal{U}_\mathcal{S}(t,t') = [\mathcal{H}_I(t) - \mathcal{S}(t)]\mathcal{U}_\mathcal{S}(t,t') \qquad \mathcal{S}(t) = \text{no-splitting operator}$$

$$\mathcal{U}_\mathcal{S}(t,t') = \mathcal{N}_\mathcal{S}(t,t') + \int_{t'}^{t} d\tau\; \mathcal{U}_\mathcal{S}(t,\tau)\mathcal{H}_I(\tau)\mathcal{N}_\mathcal{S}(\tau,t')$$

where

$$\mathcal{N}_\mathcal{S}(\tau,t') = \mathbb{T}\exp\left[-\int_{t'}^{\tau} d\tau'\;\mathcal{S}(\tau')\right]$$

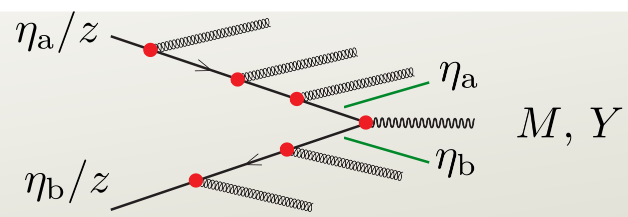


Improving parton showers by adding a few obvious corrections to a few obvious places is a very questionable approach. Beyond LL, generic parton shower problem becomes quantum. Need a reformulation of the whole approach, not an improvement of the current one.

Complex final states: better showers

Nagy

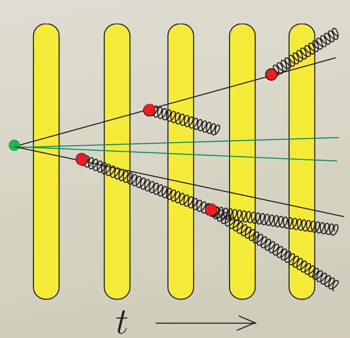
If soft radiation to the final state is restricted, soft and virtual emissions do not cancel, threshold logarithms appear and cross sections are modified. In perturbative computations, effective restriction of radiation can be provided by steeply falling PDFs as well as by external constraints. In parton showers, only the second mechanism is operational, the first does not work due to strict unitarity of the evolution.



There are logarithms of $(1-z)$:

$$\int_0^1 dz\ f_{a/A}(\eta_a/z,\mu_F^2)\left\{\delta(1-z)+C\alpha_s\left[\frac{\log(1-z)}{1-z}\right]_+ +\cdots\right\}$$

- We find simple and intuitive leading order formulas.
- This is in the context of a leading order parton shower not "NLO," "NLL" or "NNLL."
- This is implemented as part of DEDUCTOR.
- The summation applies to all hard processes.
- The shower sums the threshold logs jointly with other large logs.



Giving up on the PS unitarity in a controlled way allows us to obtain the threshold logarithms

Evolution equation

$$\big|\rho(t)\big) = \mathcal{U}_{\mathcal{S}}(t,t_0)\big|\rho(t_0)\big)$$

$\mathcal{H}_I(t)$ = splitting operato

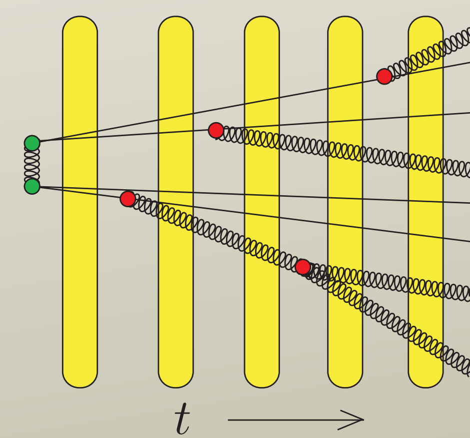
$$\frac{d}{dt}\mathcal{U}_{\mathcal{S}}(t,t') = [\mathcal{H}_I(t)-\mathcal{S}(t)]\mathcal{U}_{\mathcal{S}}(t,t')$$

$\mathcal{S}(t)$ = no-splitting operat

$$\mathcal{U}_{\mathcal{S}}(t,t') = \mathcal{N}_{\mathcal{S}}(t,t') + \int_{t'}^{t} d\tau\ \mathcal{U}_{\mathcal{S}}(t,\tau)\mathcal{H}_I(\tau)\mathcal{N}_{\mathcal{S}}(\tau,t')$$

where

$$\mathcal{N}_{\mathcal{S}}(\tau,t') = \mathbb{T}\exp\left[-\int_{t'}^{\tau} d\tau'\ \mathcal{S}(\tau')\right]$$



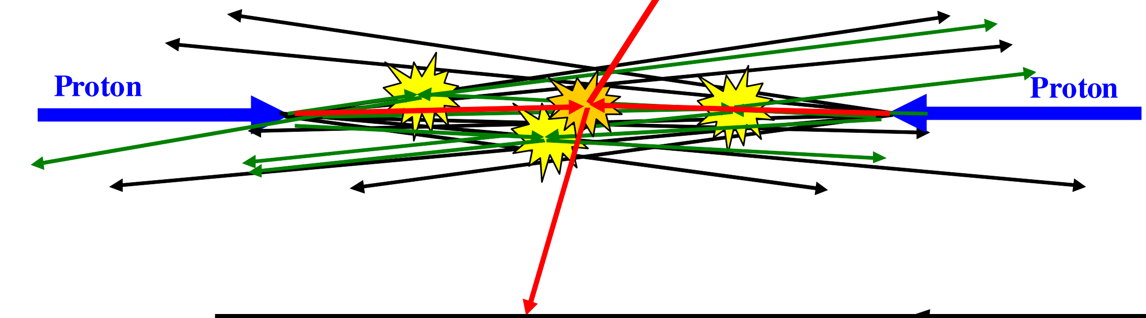
Soft resummations in a traditional context: talks by Bonvini and Wever

But every parton shower -- even the highly improved one -- has a skeleton in the closet

Universal UE-MB-DPS Tune

"Underlying Event"

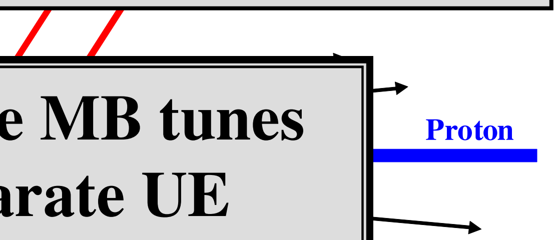
One hard scattering plus BBR & MPI



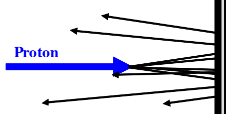
My dream!

DPS

Two hard scatterings plus BBR & MPI



"Min-



Alternatively one can produce separate MB tunes (like ATLAS Tune A2 & A3), and separate UE tunes (like ATLAS Tune A14), and separate DPS tunes (like CMS Tune CDPSTP8S2-4j).

The experimental side of me thinks this is fine.

The theoretical side of me dreams of a universal tune.

\+ …

Well, at this point the sceptical side of me strongly suggested that first-principles precision physics program at the LHC is a big bluff....

and it took a while before the optimistic side convinced me to carry on

Learning about soft physics from first principles

We may gain some insights into (some) non-perturbative physics if we understand soft and collinear emissions . In those cases, the perturbative expansion becomes complex; certain terms contain large kinematic factors -- soft and collinear logarithms. Resummations of those logarithms systematically, beyond the leading terms, is the goal of the analytic resummations

$$\alpha_s \ln^2 k_\perp \gg \alpha_s$$

Other aspects of resummations are discused in talks by Bonvini, Eber, Wever, Papaefstathiou, Rothen

Analytic understanding of parton showers in actions

Monni

Resummation in jet substructure

- Can these problems be modulated by grooming jets ?

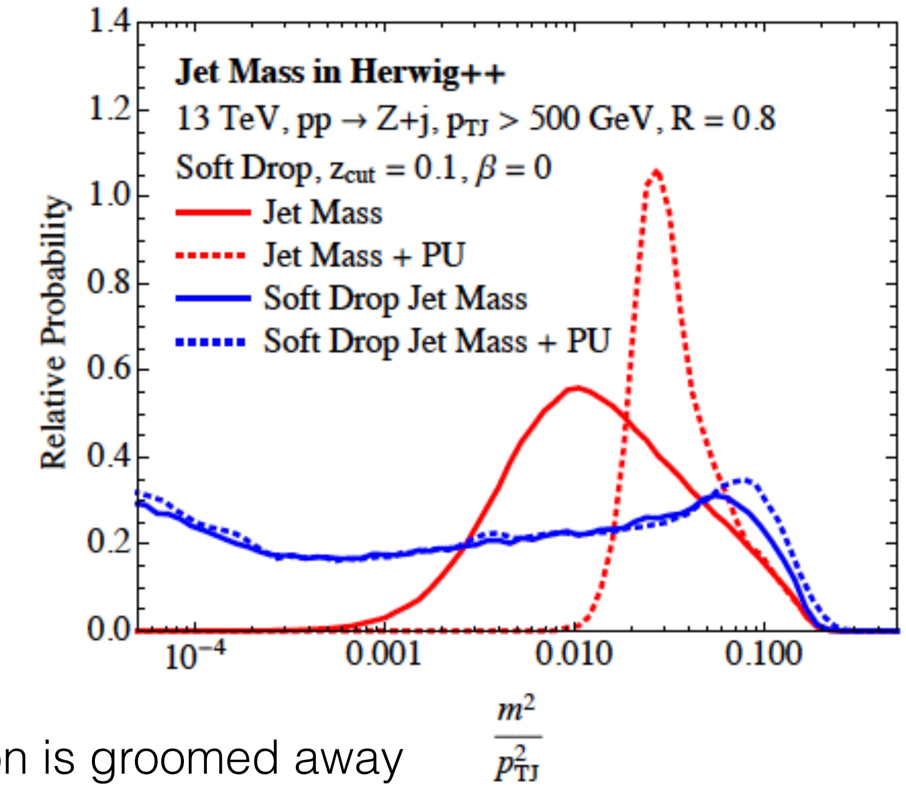
Proliferation of substructure technology in recent years

First analytic understanding at LL helped develop better-behaved observables

e.g. mMDT/Soft drop groomed jet mass:
[Dasgupta, Fregoso, Marzani, Salam '13]
[Larkoski, Marzani, Soyez, Thaler '14]

Recursive declustering of a C/A jet until

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$



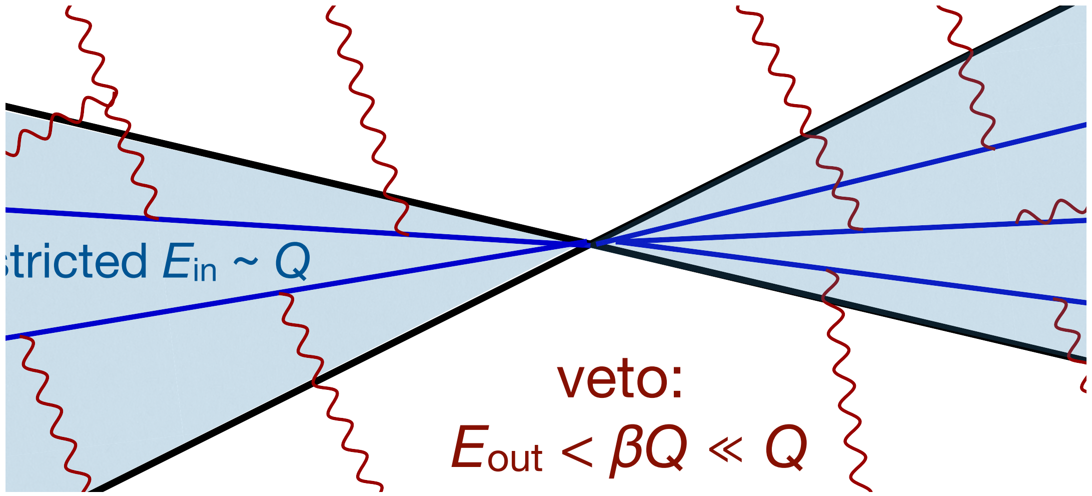
In the regime $m_J^2/p_{t,J}^2 \ll z_{\rm cut}$ the soft radiation is groomed away in a rIRC-safe way:

→ $\beta = 0$: soft logarithms (wide-angle NG, interference effects) become $\ln(z_{\rm cut})$
jet mass logarithms $\ln(m_J^2/p_{t,J}^2)$ are exclusively of collinear origin

→ $\beta \neq 0$: additional NG logs of the jet mass are power suppressed

Better analytic understanding of parton showers allows to design observables that are less affected by contamination from underlying event

Resummations and non-global logarithms



Becher

Hard function, m hard partons along fixed directions $\{n_1, \ldots, n_m\}$

Soft function with m Wilson lines

$$\sigma(\beta) = \sum_{m=2}^{\infty} \langle \boldsymbol{\mathcal{H}}_m(\{\underline{n}\}, Q, \mu) \otimes \boldsymbol{\mathcal{S}}_m(\{\underline{n}\}, Q\beta, \mu) \rangle \,,$$

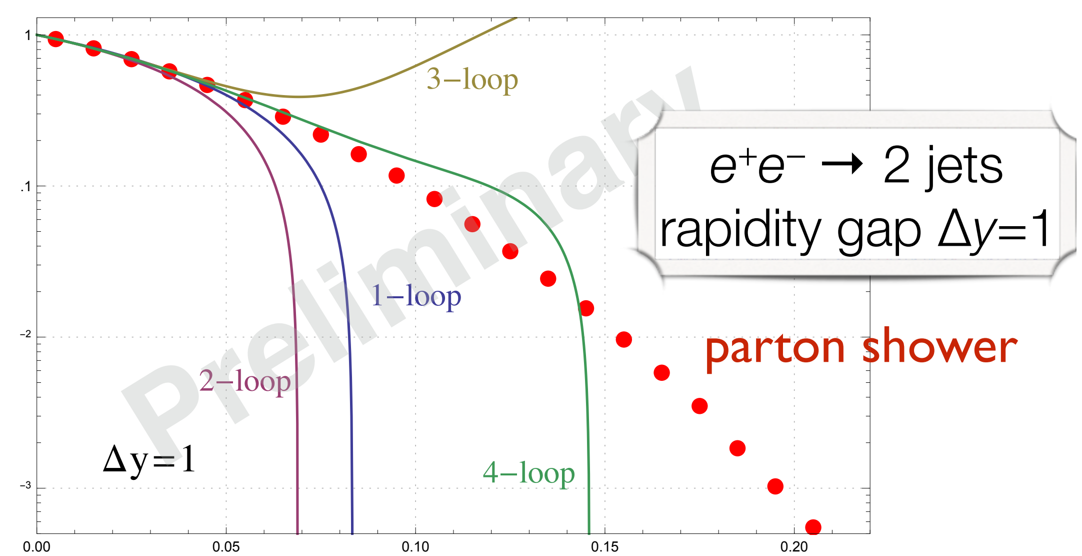
color trace

integration over the m directions

$$\boldsymbol{S}_i(n_i) = \mathbf{P} \exp\left(i g_s \int_0^\infty ds\, n_i \cdot A_s^a(s n_i)\, \boldsymbol{T}_i^a \right)$$

$$\frac{d}{d\ln\mu} \boldsymbol{\mathcal{H}}_m(Q,\mu) = -\sum_{l=2}^{m} \boldsymbol{\mathcal{H}}_l(Q,\mu)\, \boldsymbol{\Gamma}^H_{lm}(Q,\mu)$$

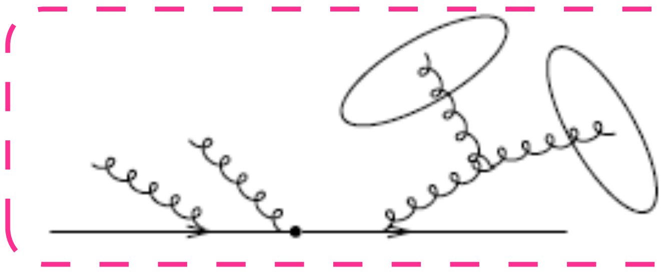
$$\boldsymbol{\mathcal{H}}_m(t) = \boldsymbol{\mathcal{H}}_m(t_1) e^{(t-t_1)V_n} + \int_{t_1}^{t} dt' \boldsymbol{\mathcal{H}}_{m-1}(t') \boldsymbol{R}_{m-1} e^{(t-t')\boldsymbol{V}_n}$$



The structure seems to be clear -- can go beyond the leading log in a systematic way !

Jet radius dependence to rule them all

Monni



- small-R jets have received some attention lately

LL resummation with generating functionals
[Dasgupta, Dreyer, Salam, Soyez '14 - '16]
Formulation in SCET: [Chien, Hornig, Lee '15]
[Kolodrubetz, Pietrulewicz, Stewart, Tackmann, Waalewijn '16]
[Kang, Ringer, Vitev '16]

- All-order effects can become relevant when R ~ 0.2-0.3 or smaller are employed (heavy ions, substructure, jet-rates studies,…)

→ • Measurements at multiple R values powerful handle to modulate hadronisation/PT effects

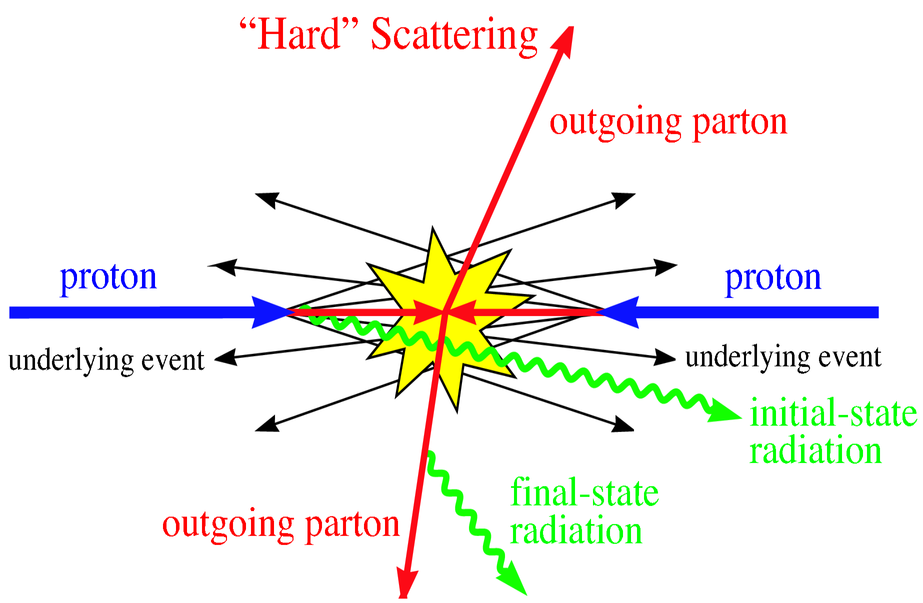
[Dasgupta, Magnea, Salam '08]

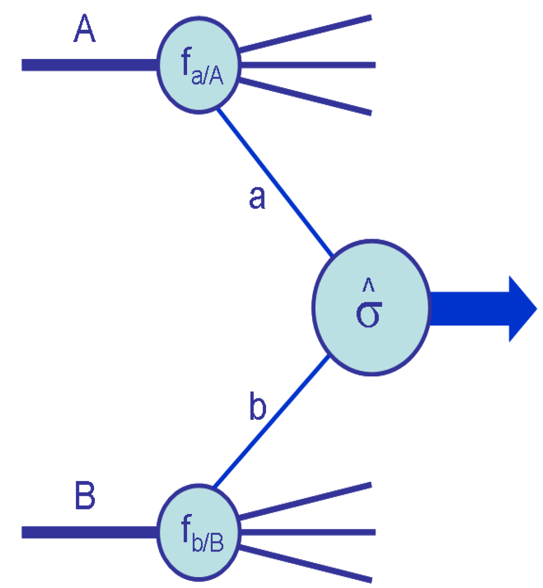
$$\mathrm{had} \sim -\frac{1}{R}\,,\ \mathrm{UE} \sim R^2\,,\ \mathrm{PT} \sim \ln\frac{1}{R}$$

One can use the dependence of jet cross sections on the jet radius to learn about different (non-perturbative) physics

Simple final states from first principles

$$d\sigma = \int dx_1 dx_2 f_i(x_1) f_j(x_2) d\sigma_{ij}(x_1, x_2) F_J \left(1 + \mathcal{O}(\Lambda_{\rm QCD}/Q)\right)$$





For relatively simple final states and/or inclusive observables, higher precision can be achieved both experimentally and theoretically.

The year of NNLO and N3LO

Talks by Caola, Huss, Lindert, Jones, Wiesemann, Currie, Trocsanyi

dijets	O(3%)	gluon-gluon, gluon-quark	PDFs, strong couplings, BSM
H+0 jet	O(3-5 %)	fully inclusive (N3LO)	Higgs couplings
H+1 jet	O(7%)	fully exclusive; Higgs decays, infinite mass tops	Higgs couplings, Higgs p_t, structure for the ggH vertex.
tT pair	O(4%)	fully exclusive, stable tops	top cross section, mass, p_t, FB asymmetry, PDFs, BSM
single top	O(1%)	fully exclusive, top decays, t-channel	V_{tb}, width, PDFs
WBF	O(1%)	exclusive, VBF cuts	Higgs couplings
W+j	O(1%)	fully exclusive, decays	PDFs
Z+j	O(1-3%)	decays, off-shell effects	PDFs
ZH	O(3-5 %)	decays to bb at NLO	Higgs couplings (H-> bb)
ZZ	O(4%)	fully exclusive	Trilinear gauge couplings, BSM
WW	O(3%)	fully exclusive	Trilinear gauge couplings, BSM
top decay	O(1-2 %)	exclusive	Top couplings
H -> bb	O(1-2 %)	exclusive, massless	Higgs couplings, boosted

What have we learned from these computations?

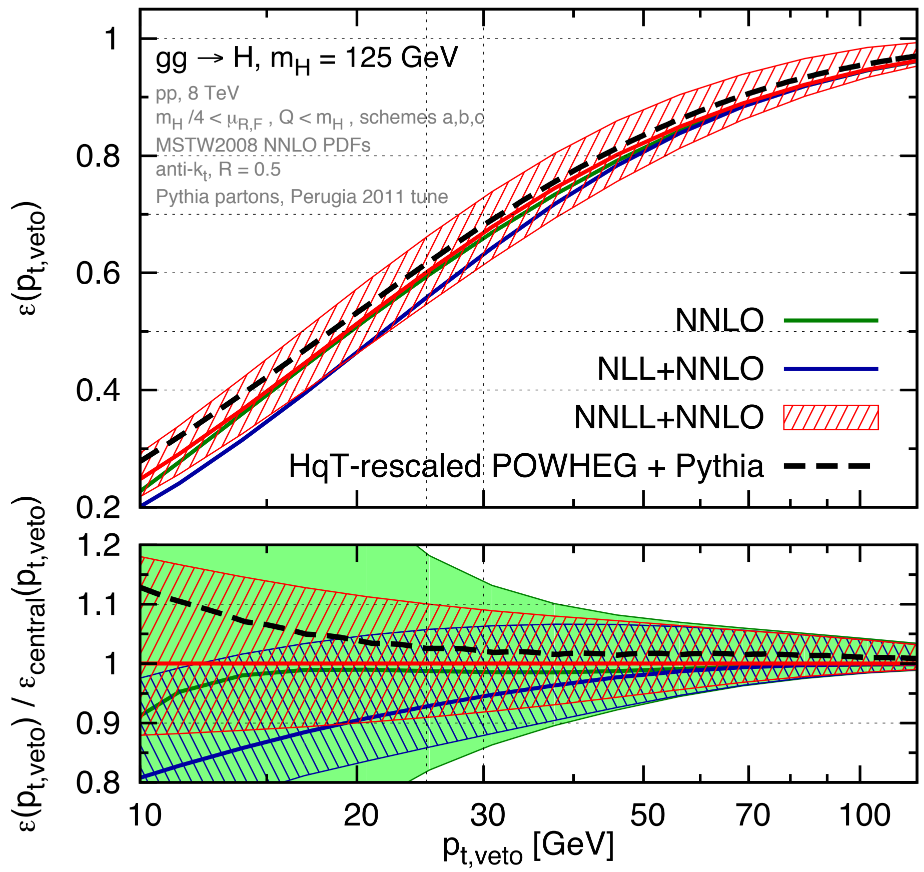
Higgs and no jets

Monni, Caola

LHC 13 TeV	$\epsilon^{\rm N^3LO+NNLL+LL_R}$	$\Sigma_{\rm 0\text{-}jet}^{\rm N^3LO+NNLL+LL_R}$ [pb]	$\Sigma_{\rm 0\text{-}jet}^{\rm N^3LO}$	$\Sigma_{\rm 0\text{-}jet}^{\rm NNLO+NNLL}$
$p_{\rm t,veto} = 25\,{\rm GeV}$	$0.539^{+0.017}_{-0.008}$	$24.7^{+0.8}_{-1.0}$	$24.3^{+0.5}_{-1.0}$	$24.6^{+2.6}_{-3.8}$
$p_{\rm t,veto} = 30\,{\rm GeV}$	$0.608^{+0.016}_{-0.007}$	$27.9^{+0.7}_{-1.1}$	$27.5^{+0.5}_{-1.1}$	$27.7^{+2.9}_{-4.0}$

LHC 13 TeV	$\Sigma_{\geq 1\text{-jet}}^{\rm NNLO+NNLL+LL_R}$ [pb]	$\Sigma_{\geq\,1\text{-jet}}^{\rm NNLO}$ [pb]
$p_{\rm t,min} = 25\,{\rm GeV}$	$21.2^{+0.4}_{-1.1}$	$21.6^{+0.5}_{-1.0}$
$p_{\rm t,min} = 30\,{\rm GeV}$	$18.0^{+0.3}_{-1.0}$	$18.4^{+0.4}_{-0.8}$

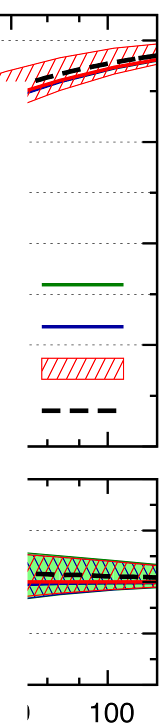
- No breakdown of fixed order perturbation theory for p_T ~ 25- 30 GeV ;
- Reliable uncertainty estimate from lower orders; residual errors O(3-5) percent for the two jet bins;
- Re-summed results change fixed-order results within the error bars of the former/latter. There seems to be little difference between re-summed and fixed order results.



Higgs and no jets

Monni, Caola

LHC 13 TeV	$\epsilon^{\mathrm{N^3LO+NNLL+LL_R}}$	$\Sigma_{\text{0-jet}}^{\mathrm{N^3LO+NNLL+LL_R}}$ [pb]	$\Sigma_{\text{0-jet}}^{\mathrm{N^3LO}}$	$\Sigma_{\text{0-jet}}^{\mathrm{NNLO+NNLL}}$
$p_{\mathrm{t,veto}} = 25\,\mathrm{GeV}$	$0.539^{+0.017}_{-0.008}$	$24.7^{+0.8}_{-1.0}$	$24.3^{+0.5}_{-1.0}$	$24.6^{+2.6}_{-3.8}$
$p_{\mathrm{t,veto}} = 30\,\mathrm{GeV}$	$0.608^{+0.016}_{-0.007}$	$27.9^{+0.7}_{-1.1}$	$27.5^{+0.5}_{-1.1}$	$27.7^{+2.9}_{-4.0}$



LHC 13 TeV
$p_{\mathrm{t,min}} = 25$ Ge
$p_{\mathrm{t,min}} = 30$ Ge

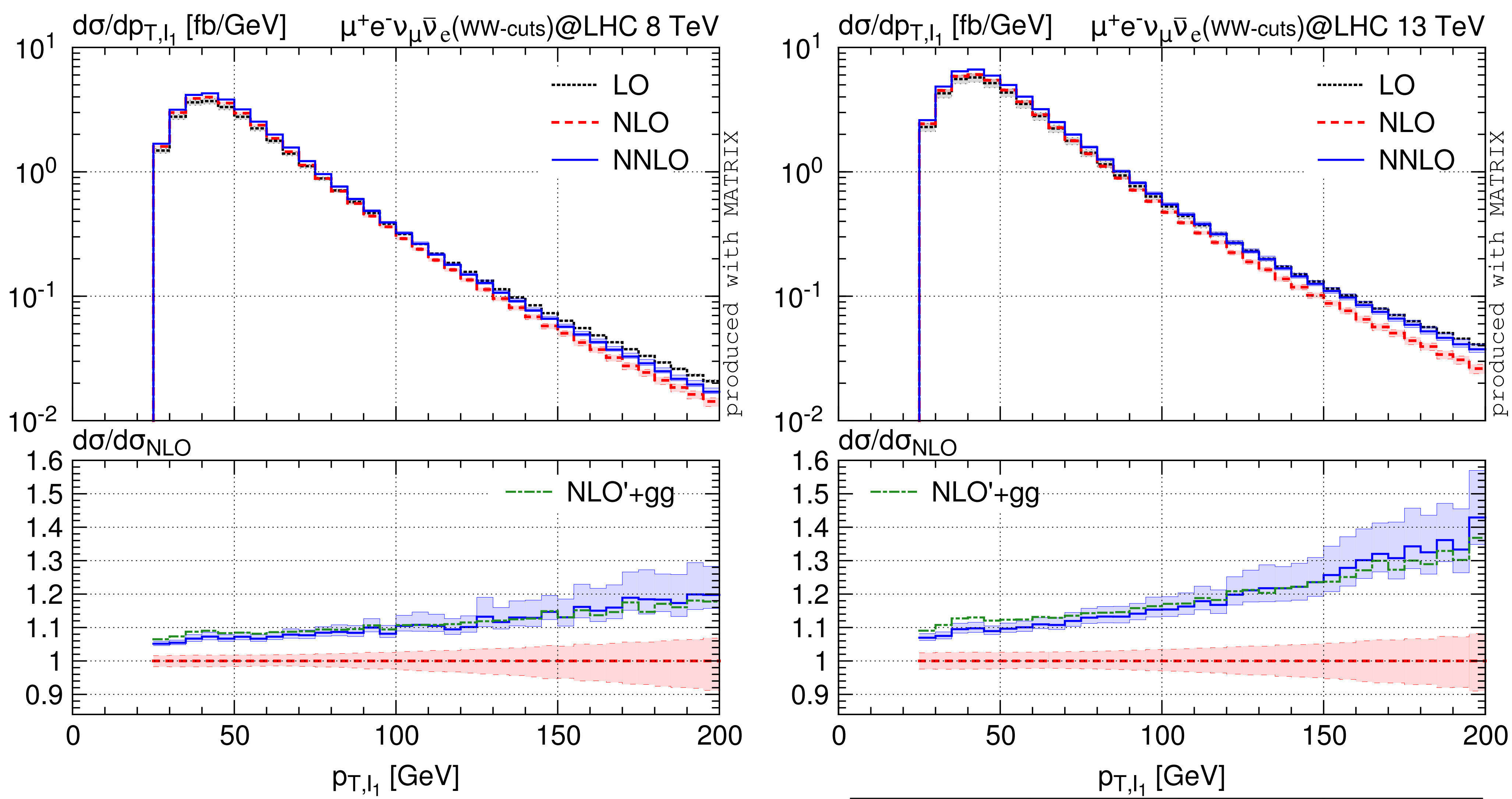
- No breakd
  for p_T ~ 25
- Reliable ur
  residual err

- Re-summed results change fixed order results within the error bars of the former/latter. There seems to be little difference between re-summed and fixed order results.

Fiducial cross sections

A very useful feature of fixed order computations is their ability to describe sensibly defined fiducial cross sections. This turns out to be quite relevant....

NNLO QCD corrections to pp -> WW fiducial cross sections are dominated by gluon fusion; the K-factor for fiducial gluon fusion is much smaller than the K-factor for the inclusive.



	$\sigma_{\mu\mu,8\ \mathrm{TeV}}$	$\sigma_{ee,8\ \mathrm{TeV}}$	$\sigma_{e\mu,8\ \mathrm{TeV}}$
$\sigma_{gg,\mathrm{LO}}$ [fb]	$5.94^{+1.89}_{-1.35}$	$5.40^{+1.71}_{-1.23}$	$9.79^{+3.13}_{-2.24}$
$\sigma_{gg,\mathrm{NLO}}$ [fb]	$7.01^{-0.36}_{-0.17}$	$6.40^{-0.32}_{-0.16}$	$11.78^{-0.46}_{-0.34}$

Talks by Wiesemann, Tancredi

Fiducial cross sections

Mistelberger

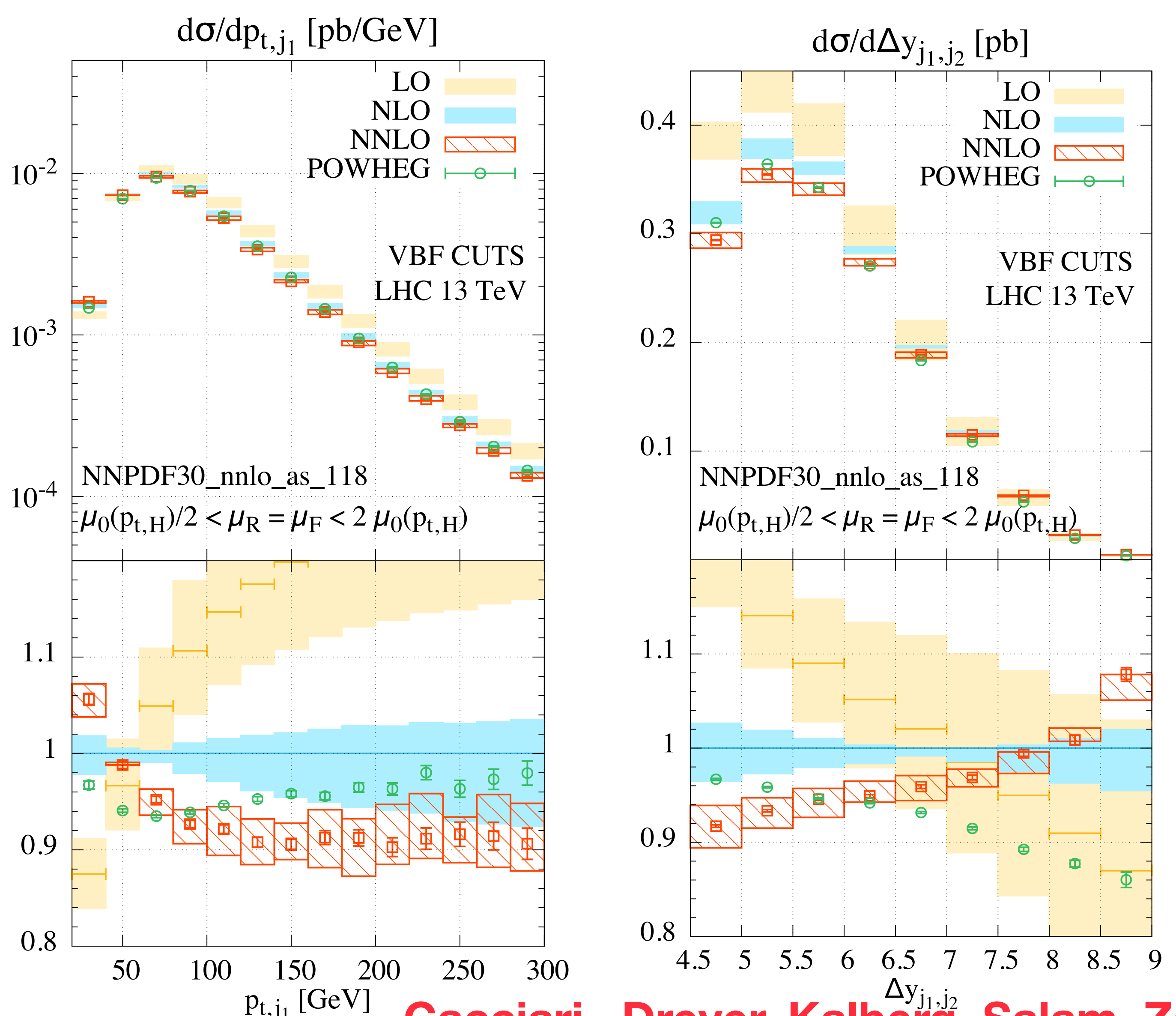
A very useful feature of fixed order computations is their ability to describe sensibly defined fiducial cross sections. This turns out to be quite relevant at the level of precision we talk about.

Quite different corrections to inclusive WBF and the WBF with particular cuts. Shapes of distributions related to jet dynamics are not captured by parton showers and NLO.

WBF cuts

$$p_\perp^{j_{1,2}} > 25\ \text{GeV}, \quad |y_{j_{1,2}}| < 4.5,$$
$$\Delta y_{j_1,j_2} = 4.5, \quad m_{j_1,j_2} > 600\ \text{GeV},$$
$$y_{j_1} y_{j_2} < 0, \quad \Delta R > 0.4$$

	σ^{nocuts}[pb]	$\sigma^{\text{VBF cuts}}$[pb]
LO	$4.032^{+0.057}_{-0.069}$	$0.957^{+0.066}_{-0.059}$
NLO	$3.929^{+0.024}_{-0.023}$	$0.876^{+0.008}_{-0.018}$
NNLO	$3.888^{+0.016}_{-0.012}$	$0.826^{+0.013}_{-0.014}$

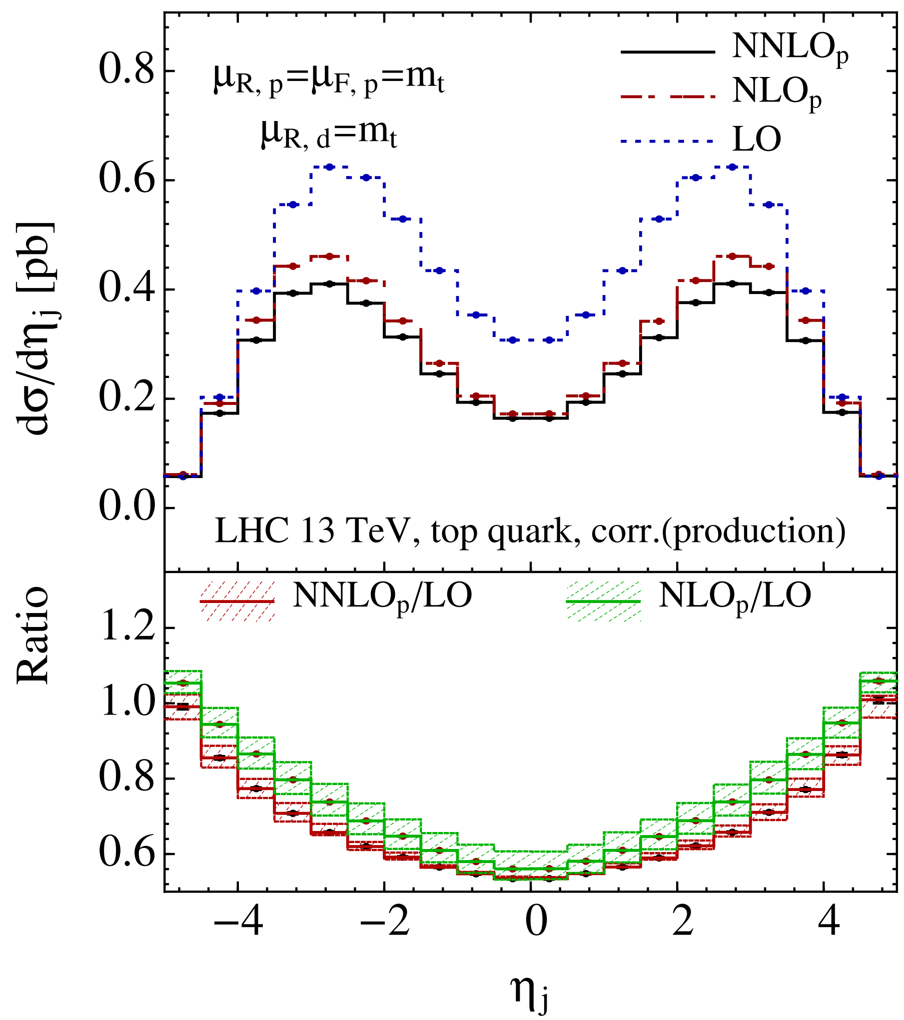


Cacciari, Dreyer, Kalberg, Salam, Zanderighi

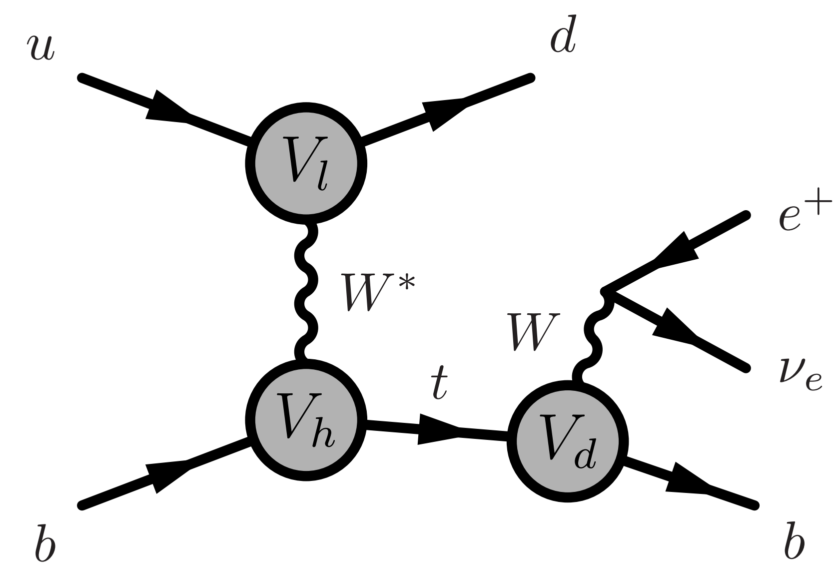
Fiducial cross sections

Talk by Frederix

A very useful feature of fixed order computations is their ability to describe sensibly defined fiducial cross sections. This turns out to be quite relevant at the level of precision we talk about.



Berger, Cao, Yuan, Zhu



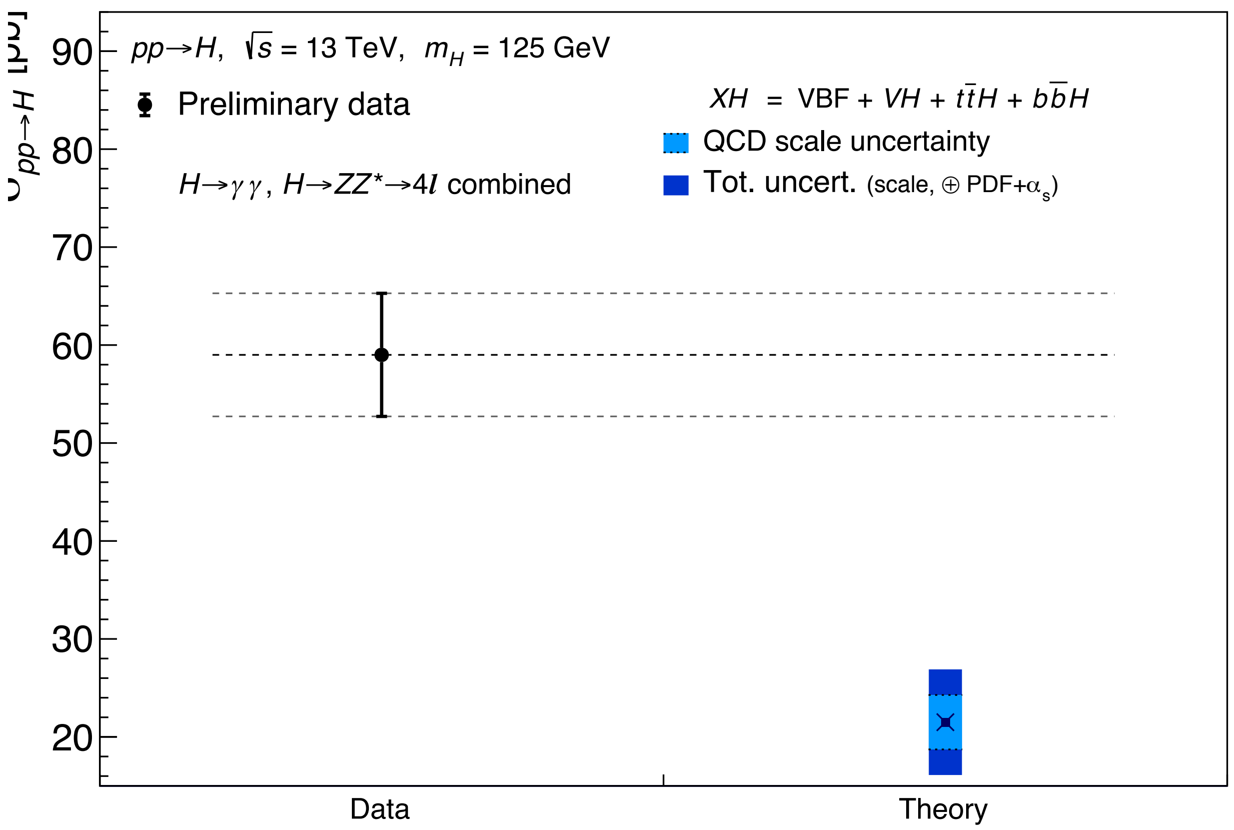
fiducial [pb]		LO	NLO	NNLO
t quark	total	$4.07^{+7.6\%}_{-9.8\%}$	$2.95^{+4.1\%}_{-2.2\%}$	$2.70^{+1.2\%}_{-0.7\%}$
	corr. in pro.		-0.79	-0.24
	corr. in dec.		-0.33	-0.13
$\bar{t}$ quark	total	$2.45^{+7.8\%}_{-10\%}$	$1.78^{+3.9\%}_{-2.0\%}$	$1.62^{+1.2\%}_{-0.8\%}$
	corr. in pro.		-0.46	-0.15
	corr. in dec.		-0.21	-0.08

A similar picture for the t-channel single top production -- very small O(1%) corrections to total cross section but become large (-19% @ NLO and -8% @ NNLO) if fiducial selection cuts (exactly two jets with pt > 40 GeV) are applied.

What can we do with these calculations?

Make sure we do not miss a large effect

COMPARE DATA TO PREDICTION



- Precise measurement
- 3.8 sigma deviation
- 1500 papers about new physics on the arXiv
- SM fails

B. Mistlberger

Make sure we do not miss a small effect

Typical BSM corrections to Higgs couplings are expected at the few percent level for O(1TeV) New Physics

$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha$$

B. Mistlberger

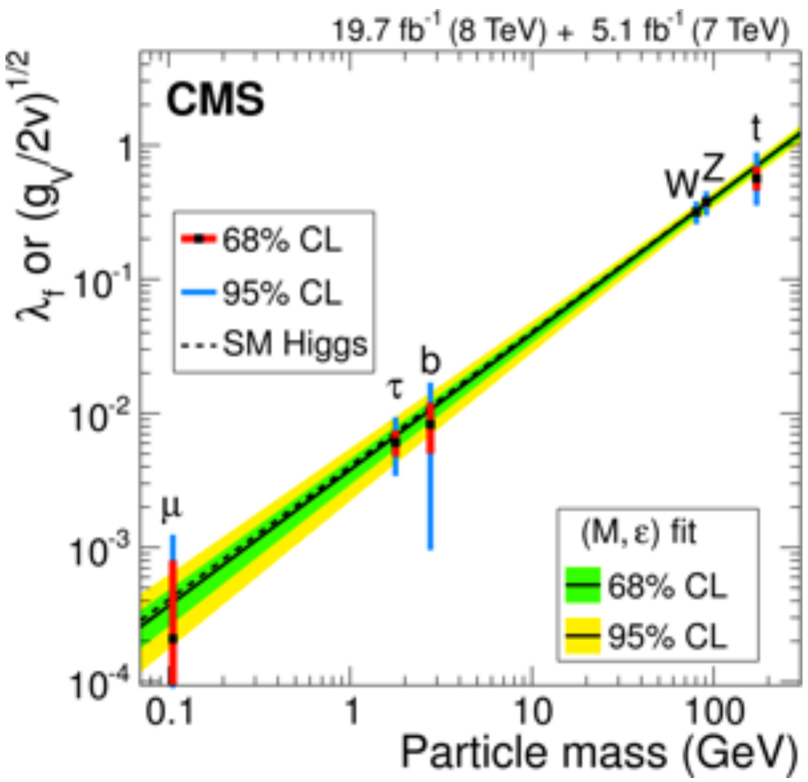
$$\begin{aligned}
48.58\,\text{pb} = &\ \ \ 16.00\,\text{pb} & (+32.9\%) & \quad (\text{LO, rEFT}) \\
&+ 20.84\,\text{pb} & (+42.9\%) & \quad (\text{NLO, rEFT}) \\
&- \ \ 2.05\,\text{pb} & (-4.2\%) & \quad ((t,b,c), \text{ exact NLO}) \\
&+ \ \ 9.56\,\text{pb} & (+19.7\%) & \quad (\text{NNLO, rEFT}) \\
&+ \ \ 0.34\,\text{pb} & (+0.7\%) & \quad (\text{NNLO}, 1/m_t) \\
&+ \ \ 2.40\,\text{pb} & (+4.9\%) & \quad (\text{EW, QCD-EW}) \\
&+ \ \ 1.49\,\text{pb} & (+3.1\%) & \quad (\text{N}^3\text{LO, rEFT})
\end{aligned}$$

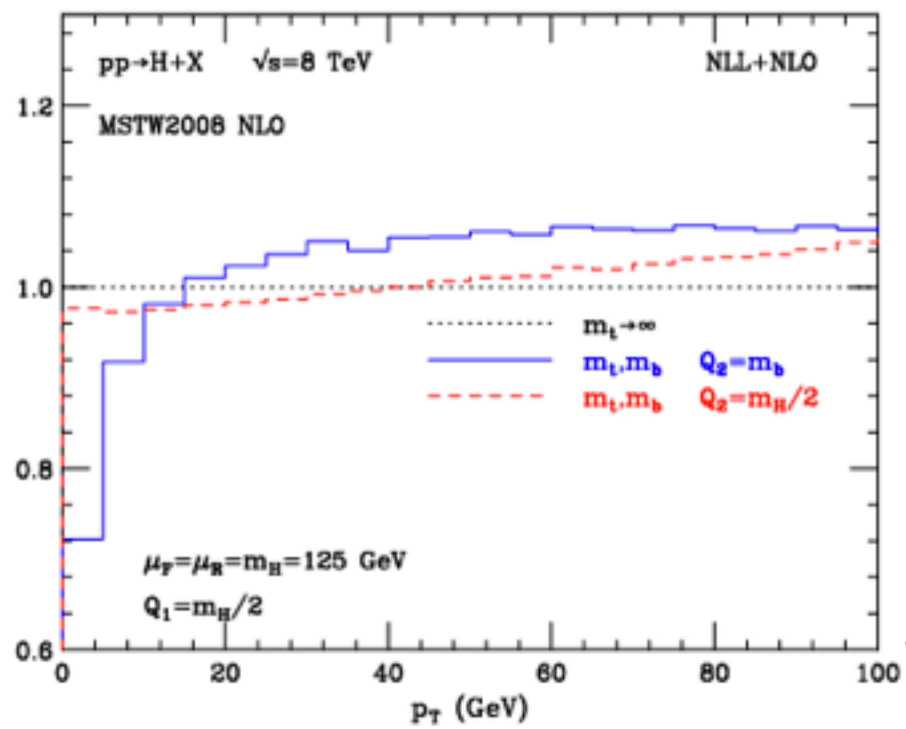
....

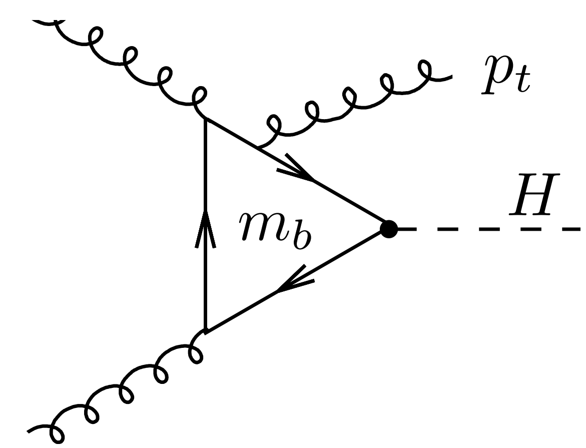
δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
+0.10 pb −1.15 pb	±0.18 pb	±0.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
+0.21% −2.37%	±0.37%	±1.16%	±1%	±0.83%	±1%

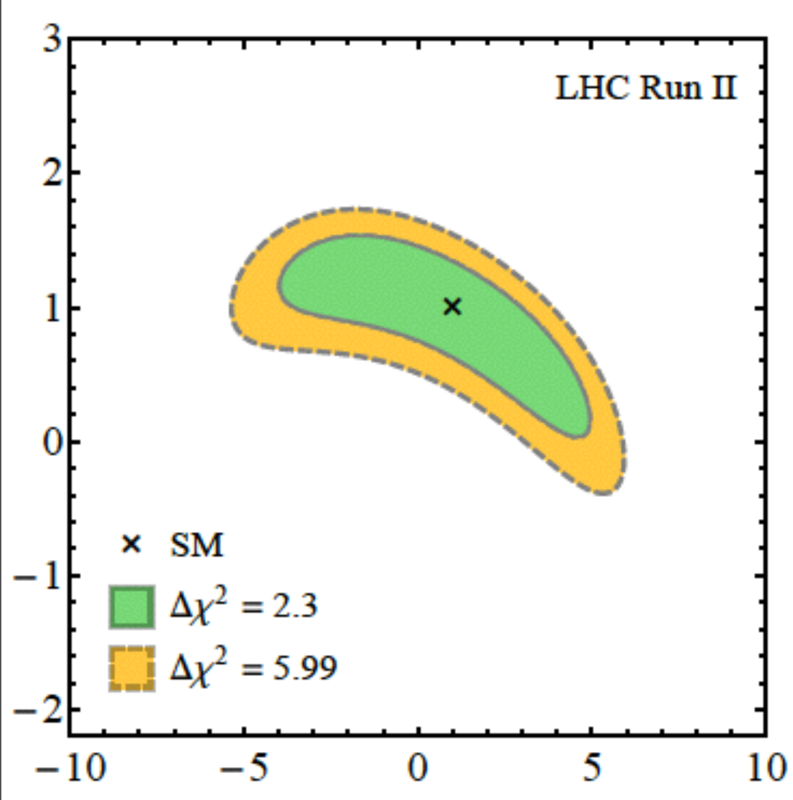
Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger

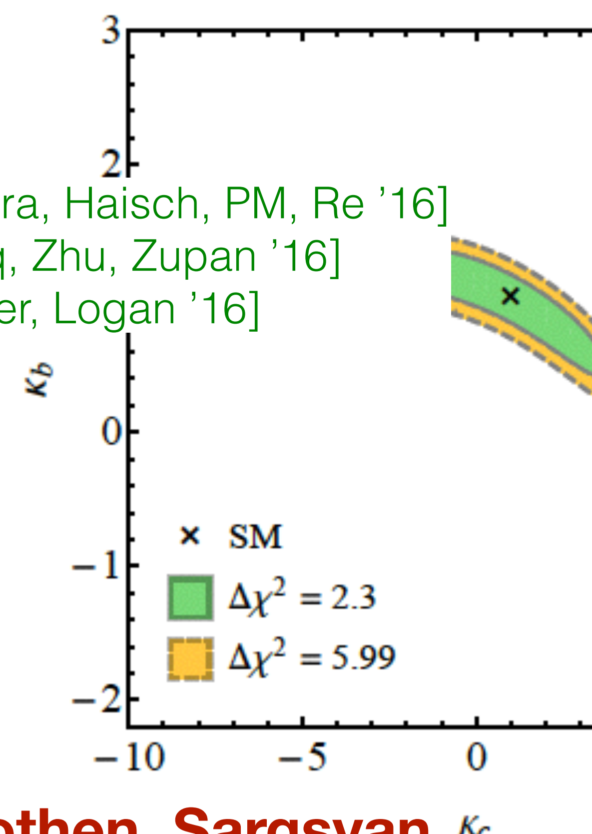
Learn about light quark Yukawa couplings



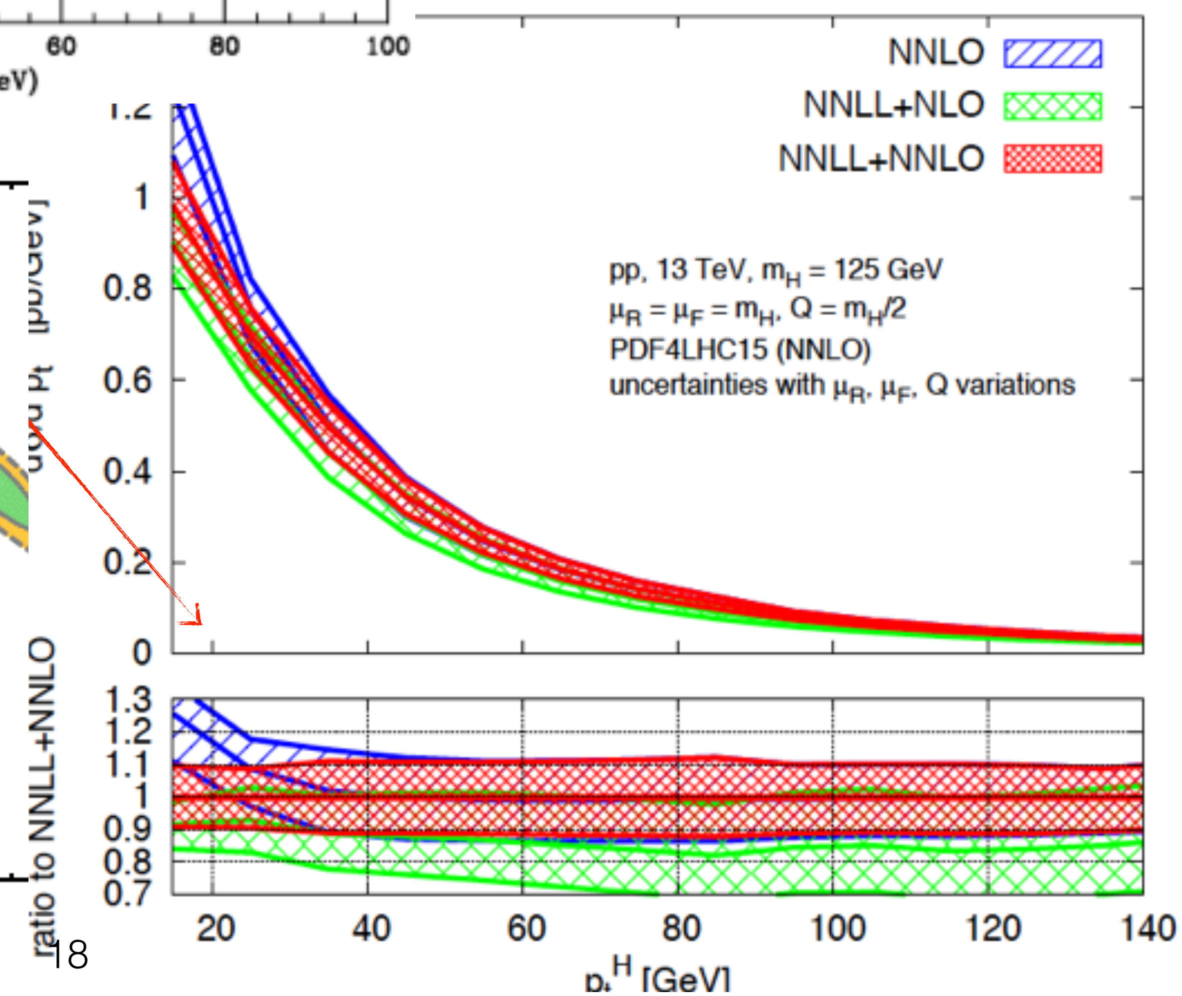








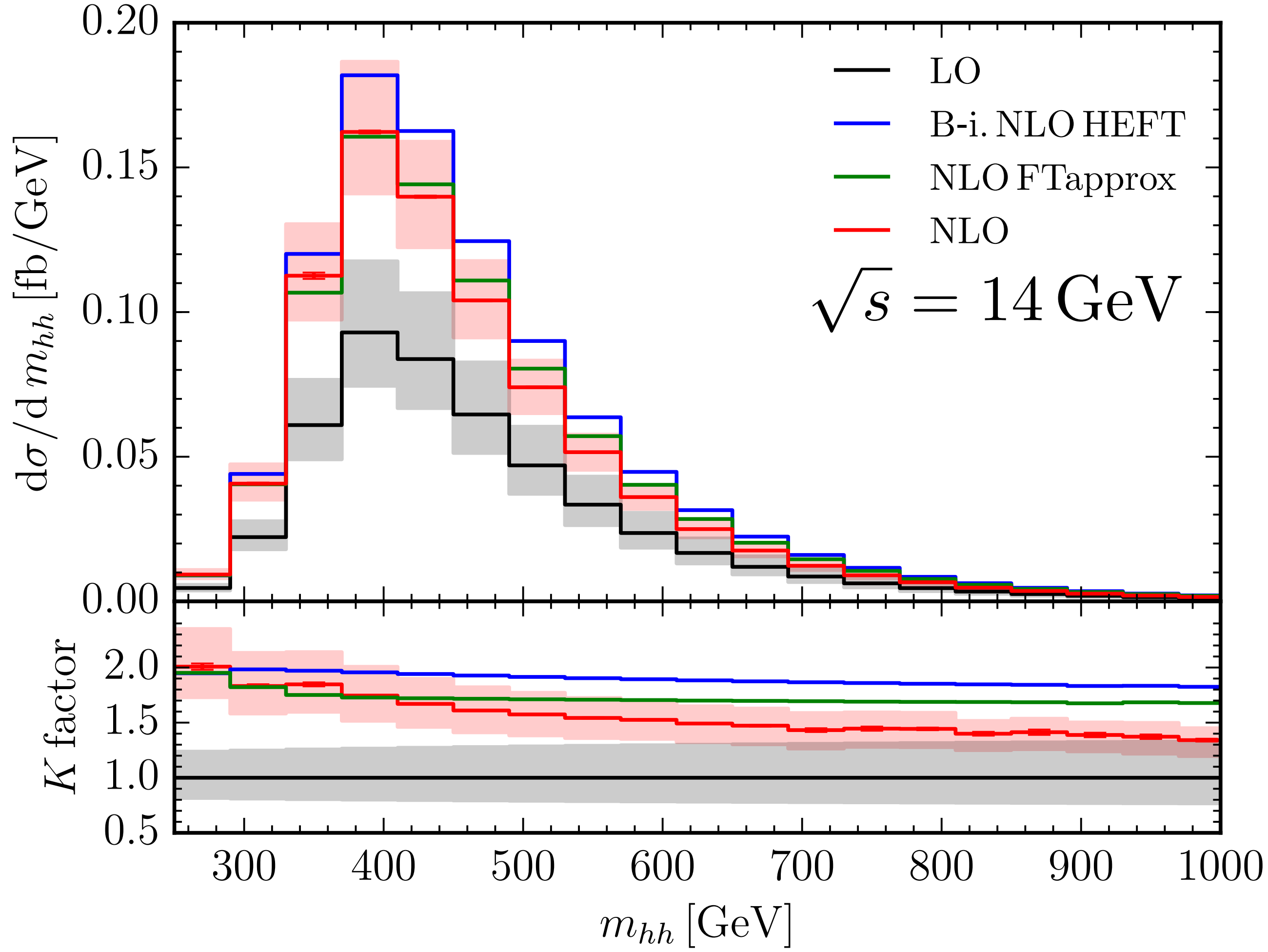
[Bishara, Haisch, PM, Re '16]
[Soreq, Zhu, Zupan '16]
[Bonner, Logan '16]



Talks by Monni, Rothen, Sargsyan

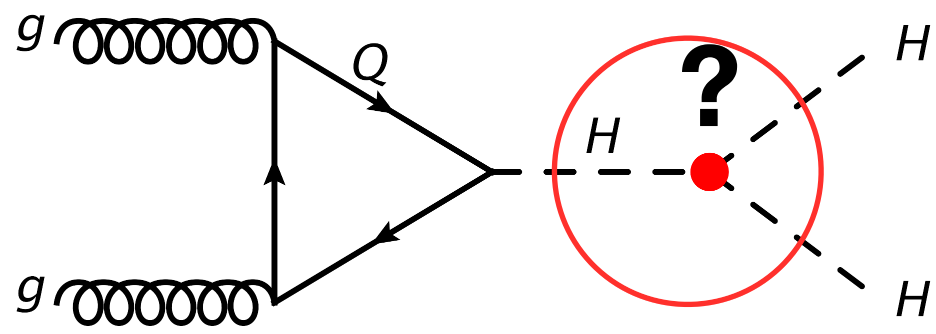
Put meaningful constraints on the Higgs boson self-coupling

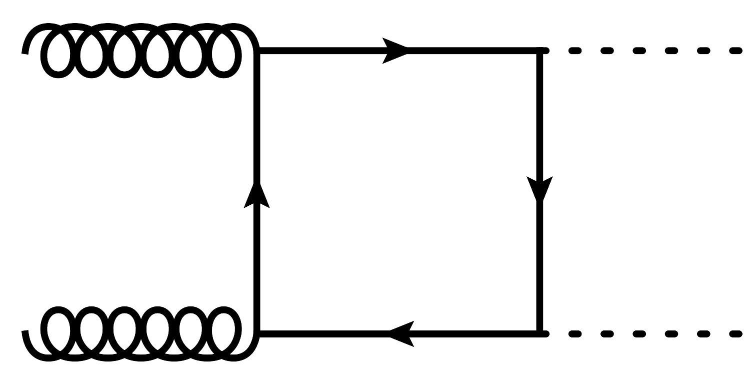
Talk by S. Jones

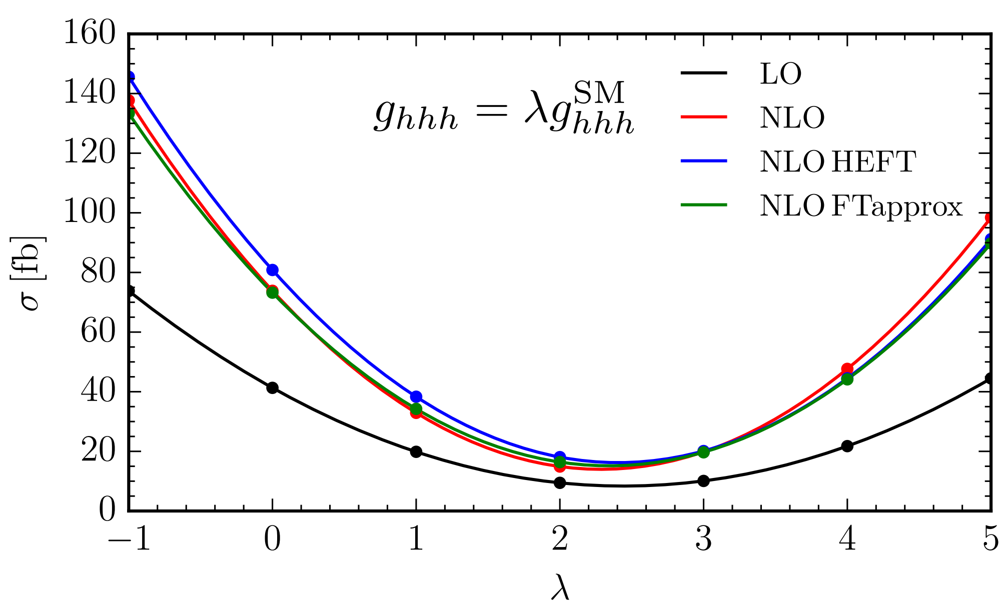


	σ_{LO} (fb)	σ_{NLO} (fb)
B.I. HEFT	$19.85^{+27.6\%}_{-20.5\%}$	$38.32^{+18.1\%}_{-14.9\%}$
FTapprox	$19.85^{+27.6\%}_{-20.5\%}$	$34.26^{+14.7\%}_{-13.2\%}$
Full Theory	$19.85^{+27.6\%}_{-20.5\%}$	**$32.91^{+13.6\%}_{-12.6\%}$**

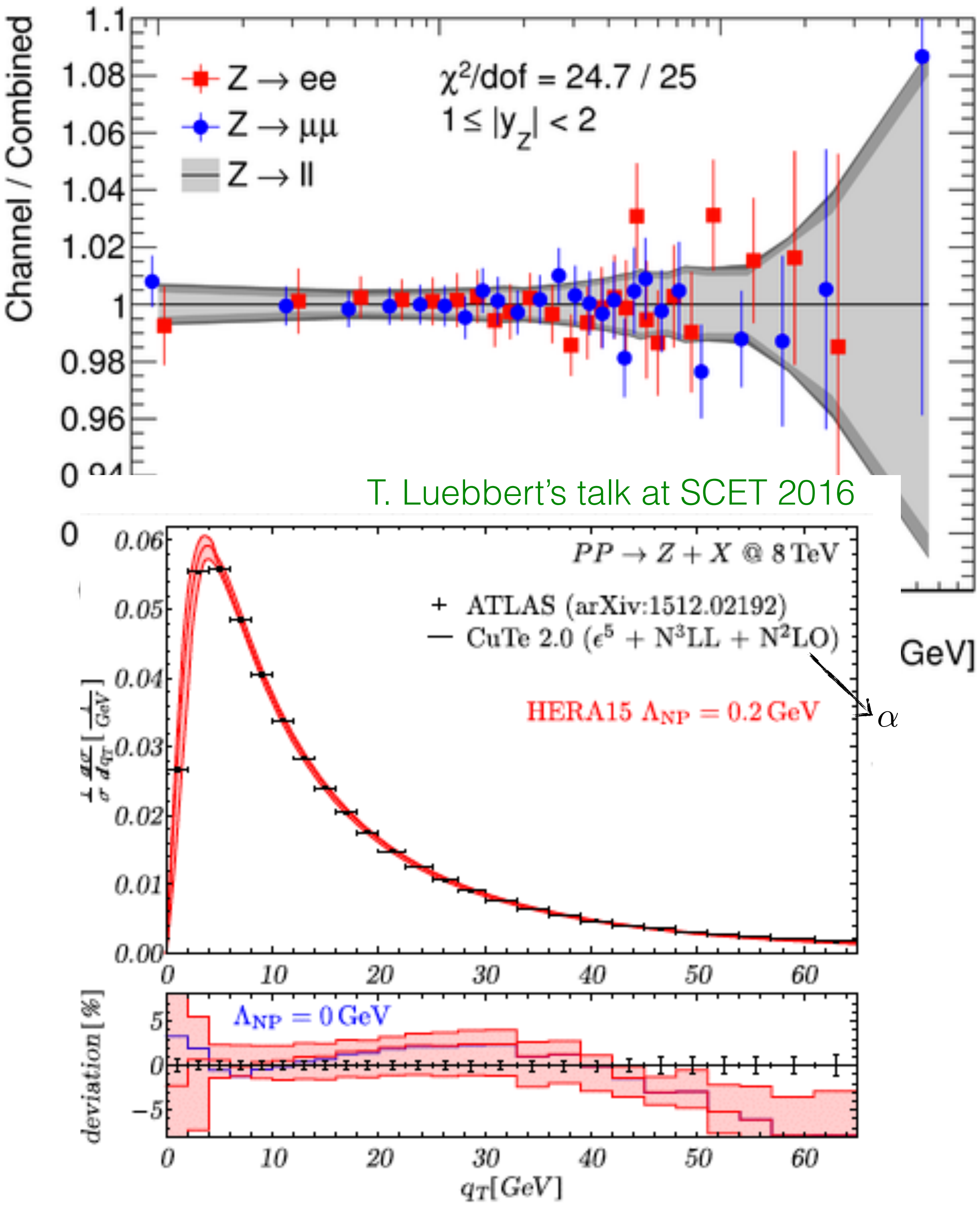
Borowka, Greiner, Heinrich, Kerner, Schenk, Schubert, Zirke







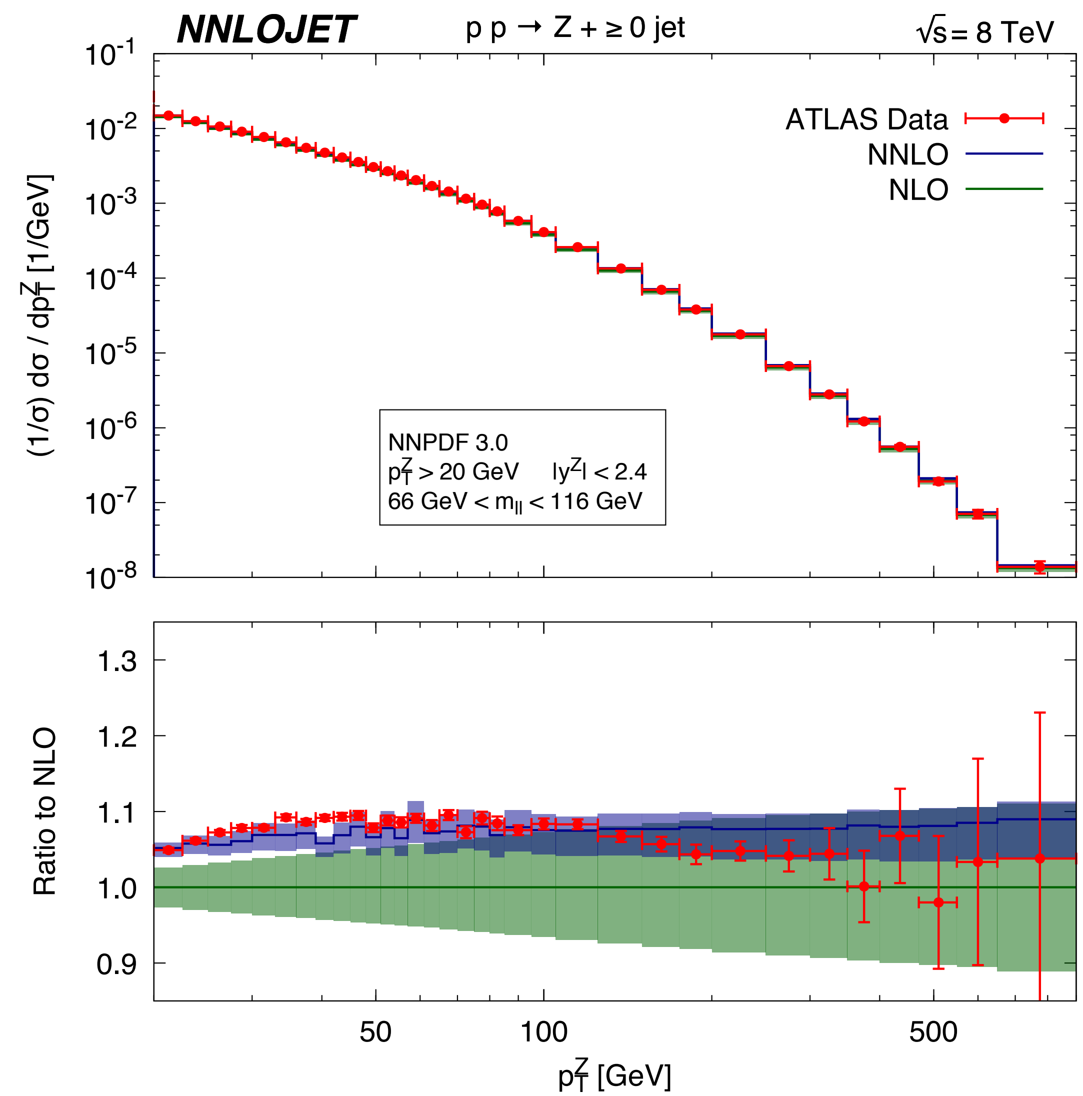
Constrain gluon PDF and/or power corrections using Z-bosons recoiling against QCD radiation



T. Luebbert's talk at SCET 2016

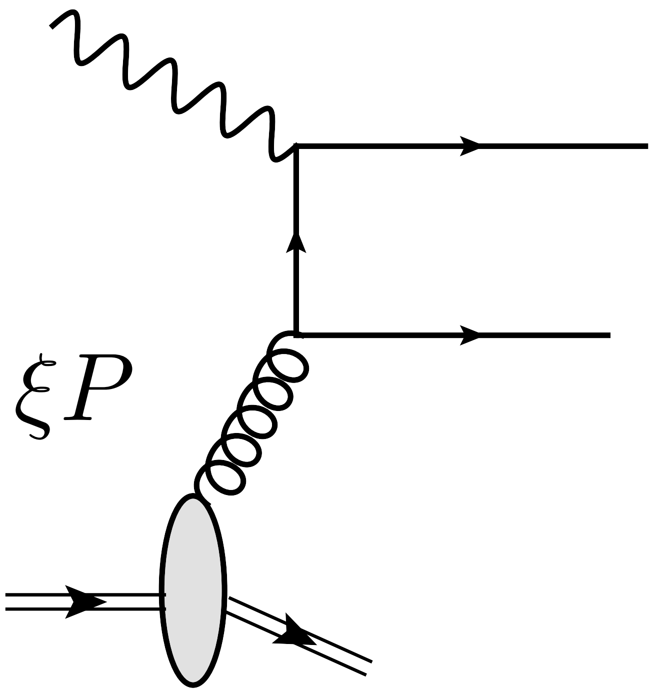
Z+jet production @NNLO

Talk by Huss

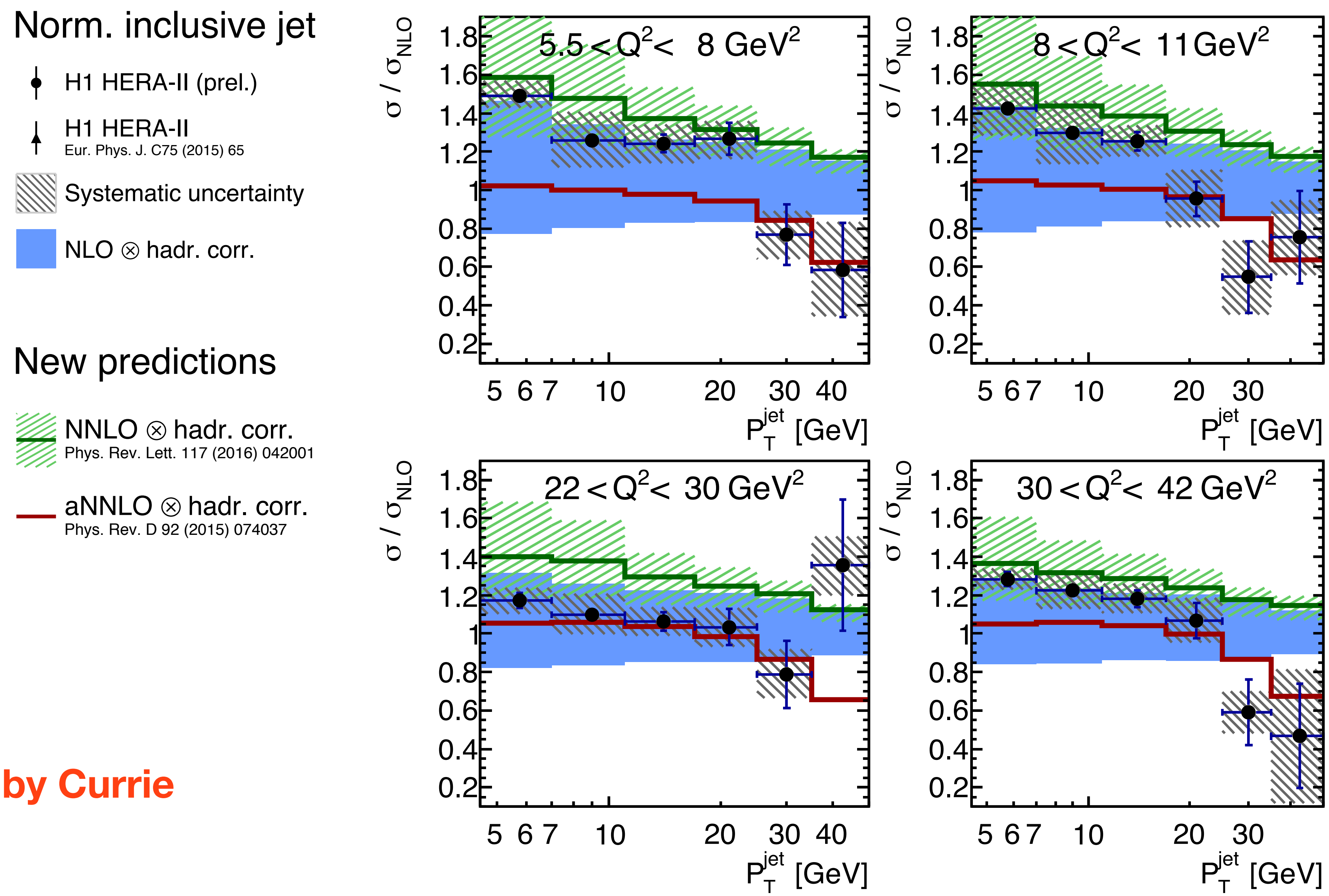


Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan

Better constrain gluon PDF and the strong coupling constant with HERA data



Jets in DIS



Talk by Currie

Gehrmann, Currie, Niehues

Inputs

Strong coupling constant

Monni, Trocsanyi, Sommer

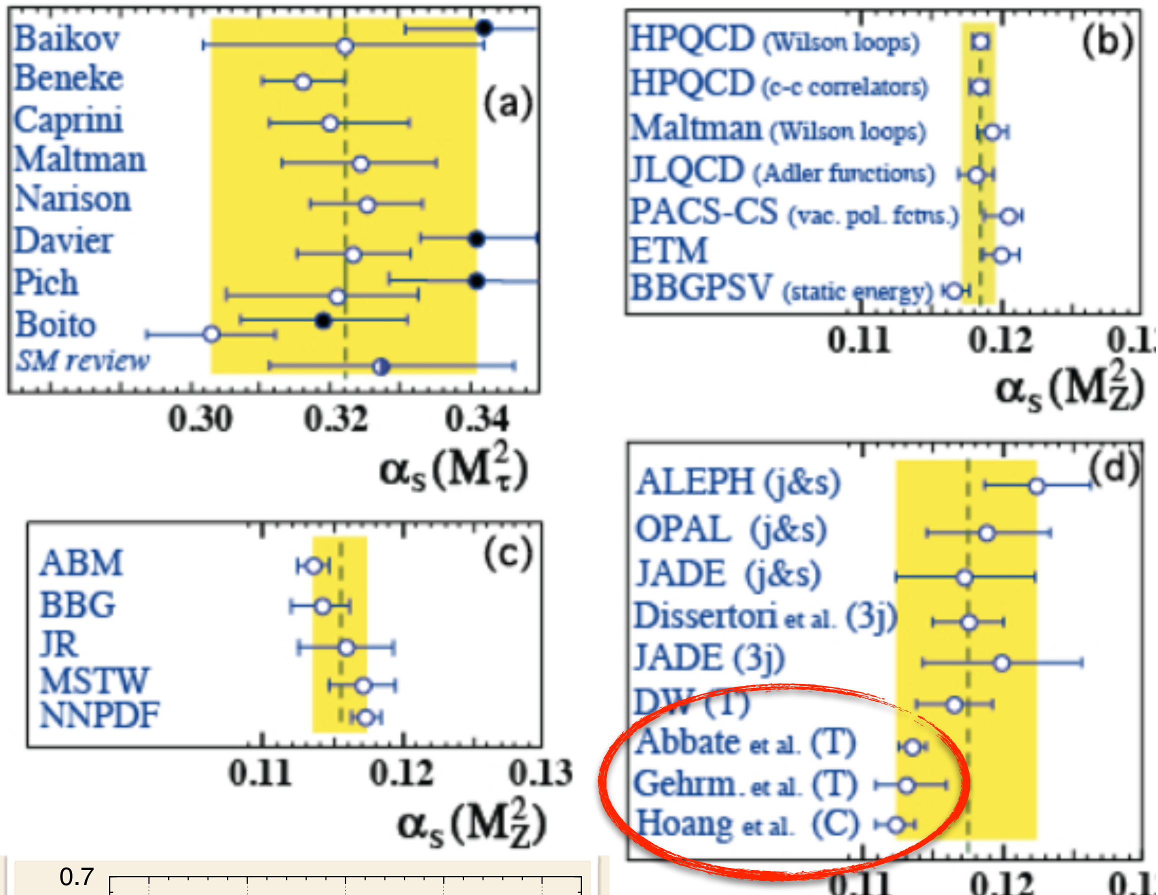
World average: [Bethke, Salam, Dissertori '15]

$\alpha_s(M_Z) = 0.1177 \pm 0.0013 (1.1\%)$ weighted

$\alpha_s(M_Z) = 0.1181 \pm 0.0013 (1.1\%)$ unweighted

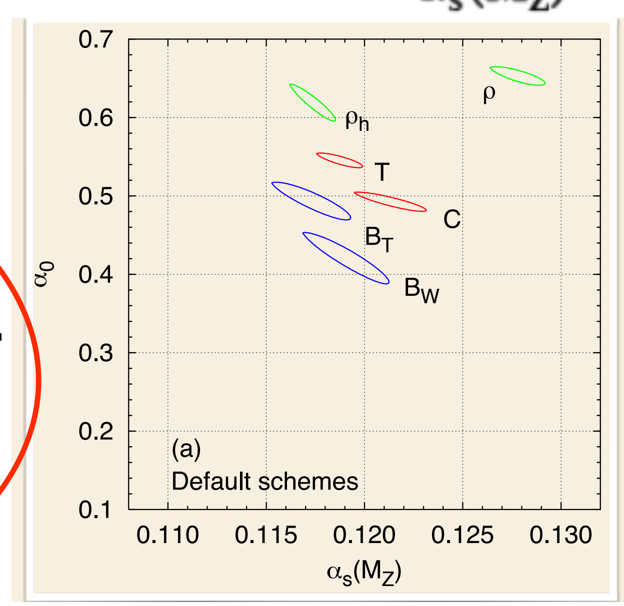
Tension between NNLL (N3LL)+NNLO extractions event-shape

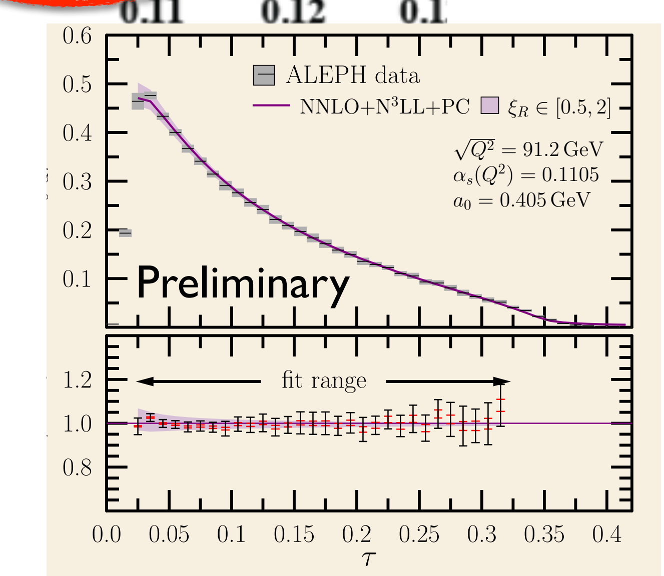
- Large tension between extractions from NNLL (N3LL)+NNLO event shapes and lattice calculations
- At LEP energies issues with high correlation between perturbative and hadronisation corrections from analytic models
- Thrust and C-parameter very similar (correlated) observables, with very same NP behaviour
- Low values of as are disfavoured by some LHC measurements



Low values of the strong coupling constant also from the DIS PDF fits.

New value from the lattice -- in agreement with the world average

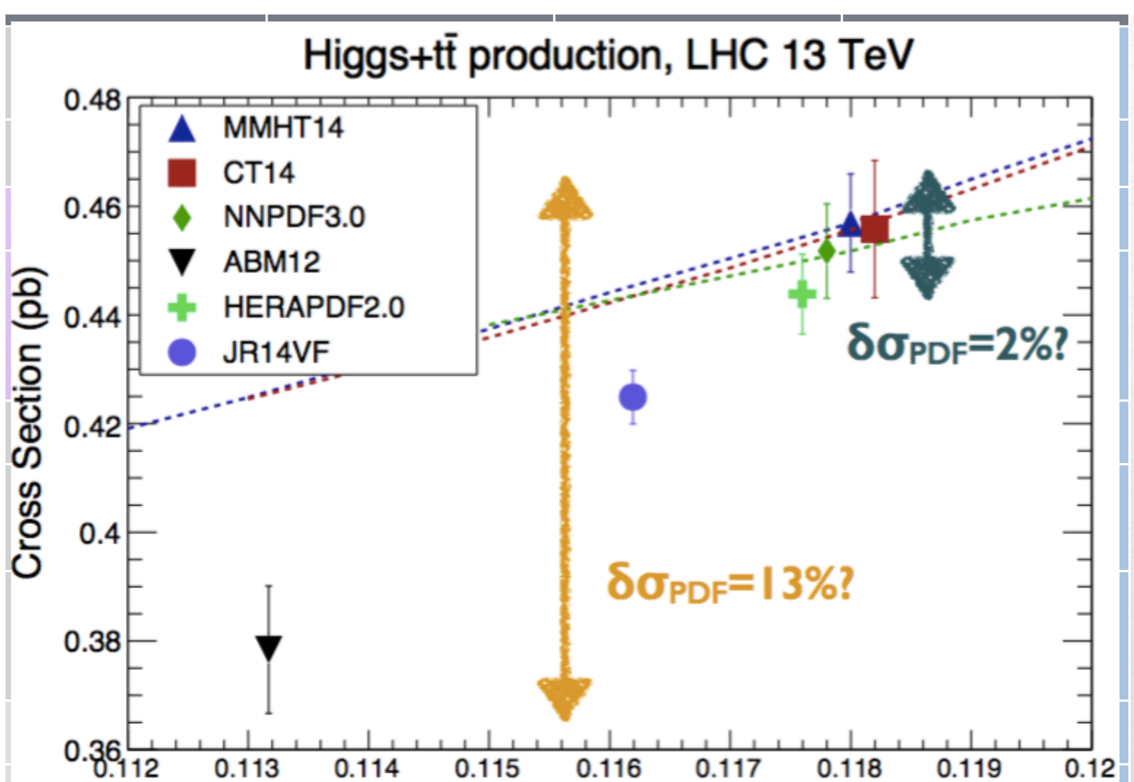




Parton distribution functions

Talks by Alekhin, Thorne, Radescu, Stump, Rojo, Bonvini

	CT14	MMHT14	NNPDF3.0	HERAPDF2.0	ABM12(ABMP)	CJ15	JR14
HQ scheme	VFNS (ACOT-χ)	VFNS (TR opt)	VFNS (FONLL)	VFNS (TR opt)	FFNS Run mc (ABM)	VFNS (ACOT)	FFNS (JR)
order in pQCD	LO, NLO, NNLO	LO, NLO, NNLO	LO, NLO, NNLO	LO, NLO, NNLO	NNLO	NLO	NLO, NNLO
α(Mz)	fixed(fitted)	fixed (fitted)	fixed	fixed	fitted	fixed	fitted
α(Mz) LO α(Mz) NLO α(Mz) NNLO	0.1300 0.1180 (0.117) 0.1180 (0.115)	0.1350 0.1180 (0.1201) 0.1180 (0.1172)	0.1180 0.1180 0.1180	0.1300 0.1180 0.1180	- - 0.1132	- 0.118 -	- 0.1158 0.1136
Nr param.	Pol. Bernst. 28	Pol. Cheb. 25	NN (259)	Pol. 14	Pol. 24	Pol. 22	Pol.25
PDF assumptions	ubar/dbar=1(x->0) u/d=1 (x->0)	s-sbar=fit. dbar-ubar=fit.	dbar-ubar=fit	ubar=dbar (x->0) sbar=0.67*dbar	s=sbar dbar-ubar=fit	dv/uv=const s+sbar=k(ubar+dbar)	dbar-ubar=fit
Stat. treatm.	Hessian 2 stages: $\Delta\chi 2$=100 90%CL region	Hessian $\Delta\chi 2$ Dynamical (68%CL)	Monte Carlo (68%CL)	Hessian $\Delta\chi 2$=1 (68%CL)	Hessian $\Delta\chi 2$=1 (68%CL)	Hessian $\Delta\chi 2$=1 (68%CL)	Hessian $\Delta\chi 2$=1 (68%CL)
Q2min	2	2	3.5	3.5	2.5	1.69	2
References	arXiv:1506.07443	arXiv:1412.3989	arXiv:1410.8849	arXiv:1506.06042	arXiv:1310.3059	arXiv:1212.1702	arXiv:1403.1852

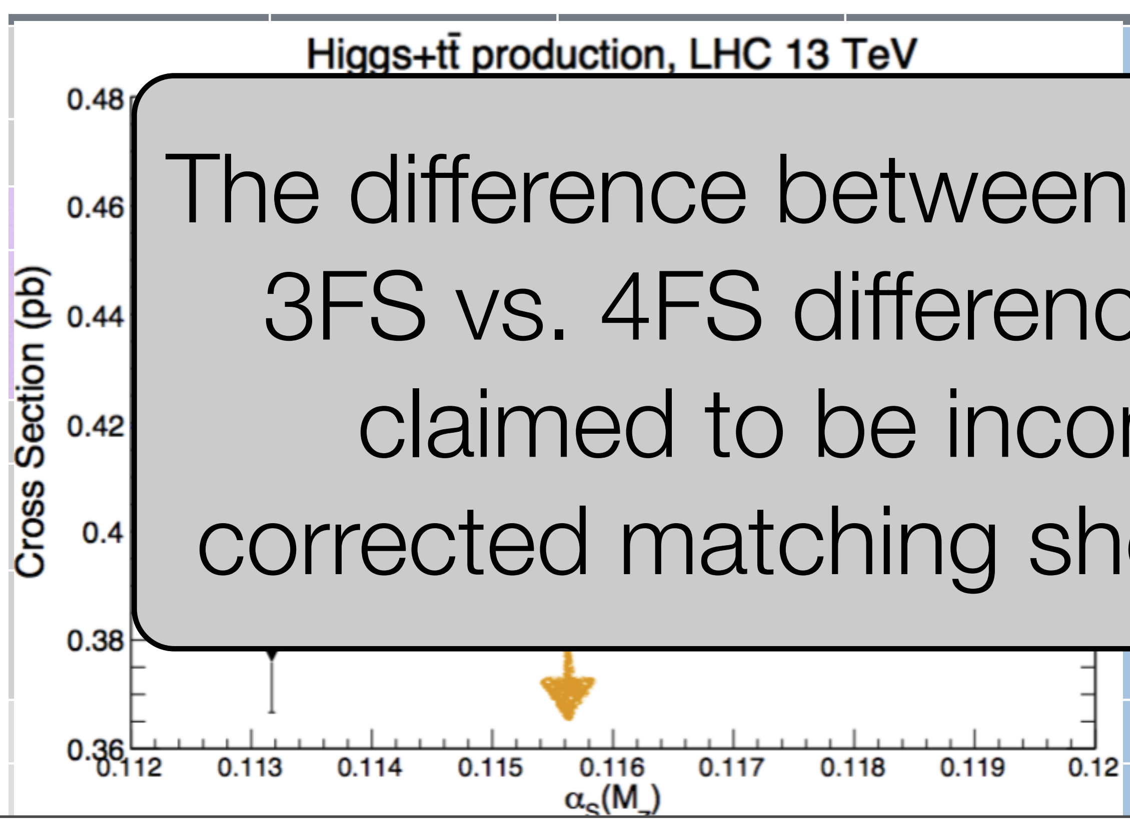


PDF sets	$\sigma(H)^{\text{NNLO}}$ [pb] nominal $\alpha_s(M_Z)$	$\sigma(H)^{\text{NNLO}}$ [pb] $\alpha_s(M_Z) = 0.115$	$\sigma(H)^{\text{NNLO}}$ [pb] $\alpha_s(M_Z) = 0.118$
ABM12 [2]	39.80 ± 0.84	41.62 ± 0.46	44.70 ± 0.50
CJ15 [1] [a]	$42.45\,^{+0.43}_{-0.18}$	$39.48\,^{+0.40}_{-0.17}$	$42.45\,^{+0.43}_{-0.18}$
CT14 [3] [b]	$42.33\,^{+1.43}_{-1.68}$	$39.41\,^{+1.33}_{-1.56}$ (40.10)	$42.33\,^{+1.43}_{-1.68}$
HERAPDF2.0 [4] [c]	$42.62\,^{+0.35}_{-0.43}$	$39.68\,^{+0.32}_{-0.40}$ (40.88)	$42.62\,^{+0.35}_{-0.43}$
JR14 (dyn) [5]	38.01 ± 0.34	39.34 ± 0.22	42.25 ± 0.24
MMHT14 [6]	$42.36\,^{+0.56}_{-0.78}$	$39.43\,^{+0.53}_{-0.73}$ (40.48)	$42.36\,^{+0.56}_{-0.78}$
NNPDF3.0 [7]	42.59 ± 0.80	39.65 ± 0.74 (40.74 ± 0.88)	42.59 ± 0.80
PDF4LHC15 [8]	42.42 ± 0.78	39.49 ± 0.73	42.42 ± 0.78

Parton distribution functions

Talks by Alekhin, Thorne, Radescu, Stump

	CT14	MMHT14	NNPDF3.0	HERAPDF2.0	ABM12(ABMP)	CJ15	JR14
HQ scheme	VFNS (ACOT-χ)	VFNS (TR opt)	VFNS (FONLL)	VFNS (TR opt)	FFNS Run mc (ABM)	VFNS (ACOT)	FFNS (JR)
order in pQCD	LO, NLO, NNLO	LO, NLO, NNLO	LO, NLO, NNLO	LO, NLO, NNLO	NNLO	NLO	NLO, NNLO
α(Mz)	fixed(fitted)	fixed (fitted)	fixed	fixed	fitted	fixed	fitted
α(Mz) LO α(Mz) NLO α(Mz) NNLO	0.1300 0.1180 (0.117) 0.1180 (0.115)	0.1350 0.1180 (0.1201) 0.1180 (0.1172)	0.1180 0.1180 0.1180	0.1300 0.1180 0.1180	- - 0.1132	- 0.118 -	- 0.1158 0.1136
Nr param.	Pol. Bernst. 28	Pol. Cheb. 25	NN (259)	Pol. 14	Pol. 24	Pol. 22	Pol.25
PDF assumptions	ubar/dbar=1(x->0) u/d=1 (x->0)	s-sbar=fit. dbar-ubar=fit.	dbar-ubar=fit	ubar=dbar (x->0) sbar=0.67*dbar	s=sbar dbar-ubar=fit	dv/uv=const s+sbar=k(ubar+dbar)	dbar-ubar=fit
Stat. treatm.	Hessian 2 stages: Δχ2=100 90%CL region	Hessian Δχ2 Dynamical (68%CL)	Monte Carlo (68%CL)	Hessian Δχ2=1 (68%CL)	Hessian Δχ2=1 (68%CL)	Hessian Δχ2=1 (68%CL)	Hessian Δχ2=1 (68%CL)
Q2min	2	2	3.5	3.5	2.5	1.69	2
References	arXiv:1506.07443	arXiv:1412.3989	arXiv:1410.8849	arXiv:1506.06042	arXiv:1310.3059	arXiv:1212.1702	arXiv:1403.1852

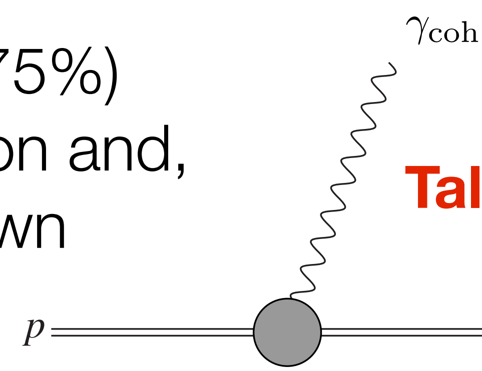


PDF sets	$\sigma(H)^{NNLO}$ [pb]	$\sigma(H)^{NNLO}$ [pb]	$\sigma(H)^{NNLO}$ [pb]
			...18
		(40.74 ± 0.88)	
PDF4LHC15 [8]	42.42 ± 0.78	39.49 ± 0.73	42.42 ± 0.78

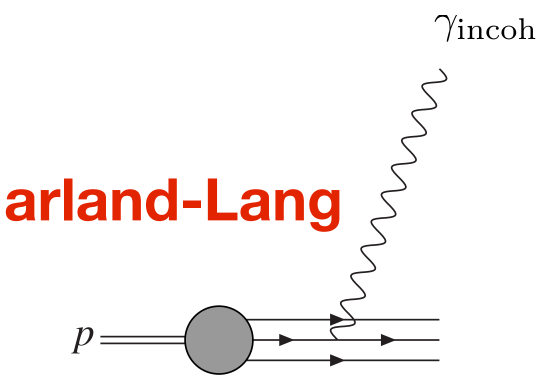
The difference between ABM and others is real; it is 3FS vs. 4FS difference. The matching in 4FS is claimed to be incomplete; the hope is that corrected matching should push PDF sets closer.

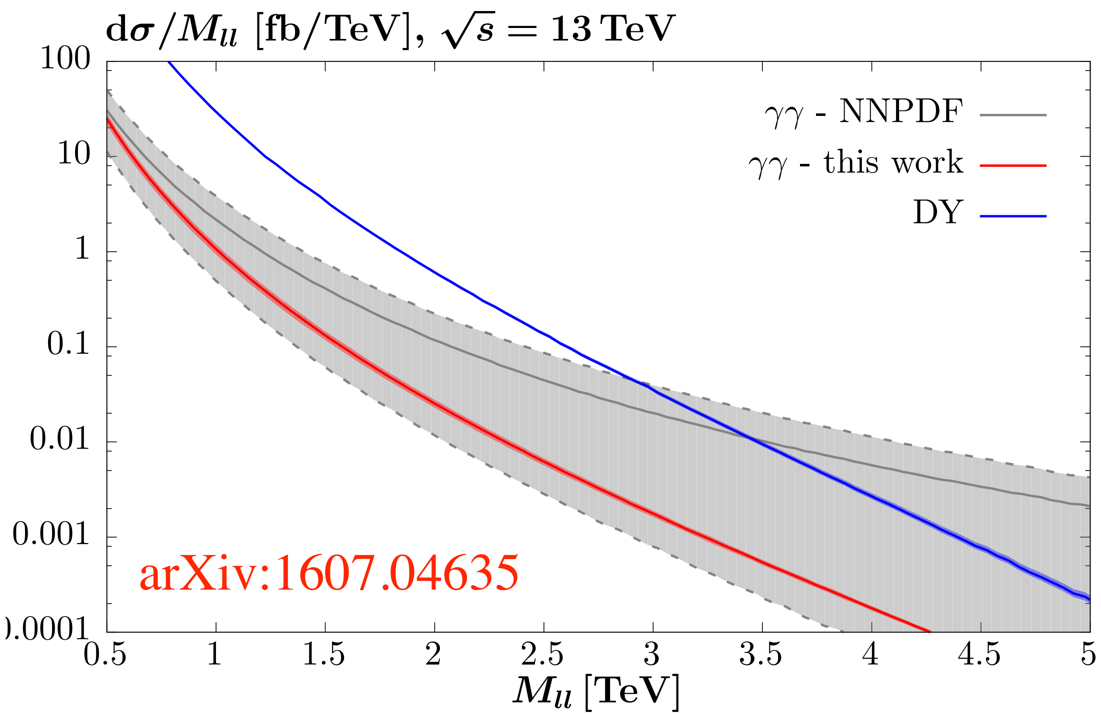
Parton distribution functions: the photon PDF

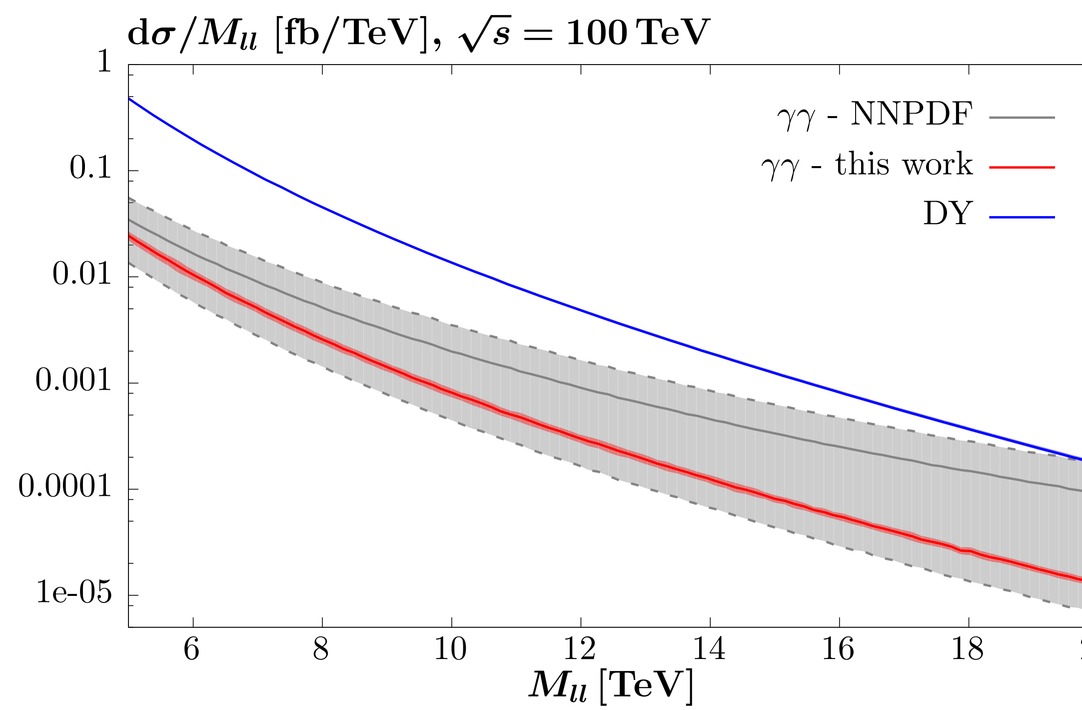
Photon PDF is very different since it has large (75%) elastic contribution known with absolute precision and, practically, no evolution/Sudakov effects of its own since the fine structure constant is tiny.



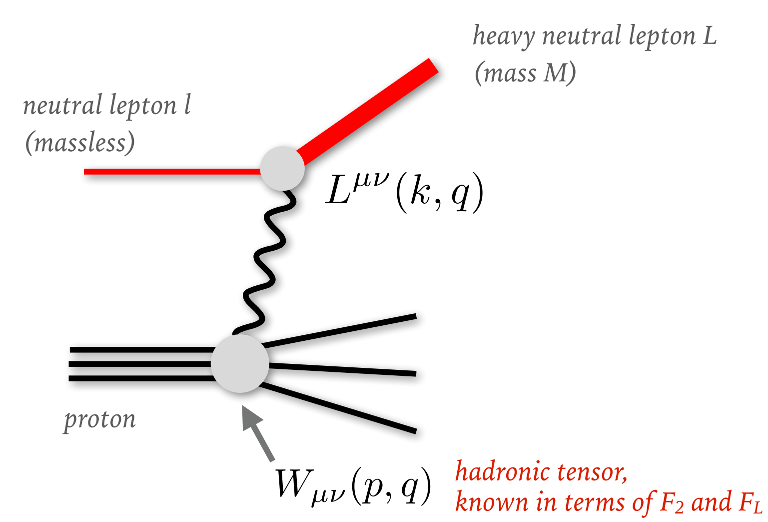
Talk by Harland-Lang





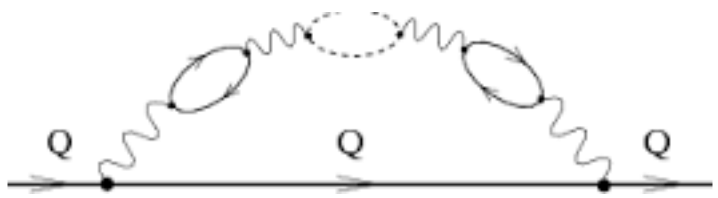


$$xf_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{dz}{z}\left\{\int_{\frac{x^2m_p^2}{1-z}}^{\frac{\mu^2}{1-z}}\frac{dQ^2}{Q^2}\alpha^2(Q^2)\left[\left(zp_{\gamma q}(z)+\frac{2x^2m_p^2}{Q^2}\right)F_2(x/z,Q^2) - z^2F_L\left(\frac{x}{z},Q^2\right)\right] - \alpha^2(\mu^2)z^2F_2\left(\frac{x}{z},\mu^2\right)\right\}, \quad (6)$$



Manohar, Nason, Salam, Zanderighi

The top quark mass



$$m_{t,\text{pole}} = (163.643 + 7.557 + 1.617 + 0.501 + 0.195)\ \text{GeV}$$

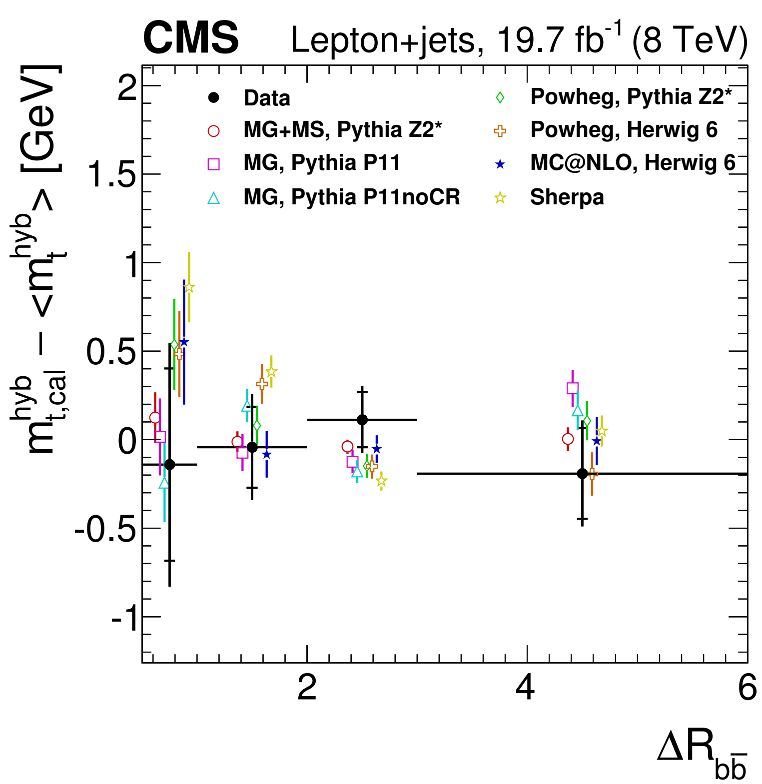
Marquard, Smirnov, Smirnov, Steinhauser; Beneke, Nason

The renormalon uncertainty in the pole mass does not exceed O(90) MeV!

New matched/merged calculations that in principle allow the choice of well-definite mass do not quite help to resolve the issue of the MC mass vs. the Lagrangian mass. The issue is really non-perturbative effects in fitted observables.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M} \approx T(M, m_t, \alpha_s)\left[1 + c\left(\frac{\Lambda_{\text{QCD}}}{M}\right)^n\right]$$

$$\delta m_t \sim \frac{c\, m_t}{k}\left(\frac{\Lambda_{\text{QCD}}}{m_t}\right)^n$$



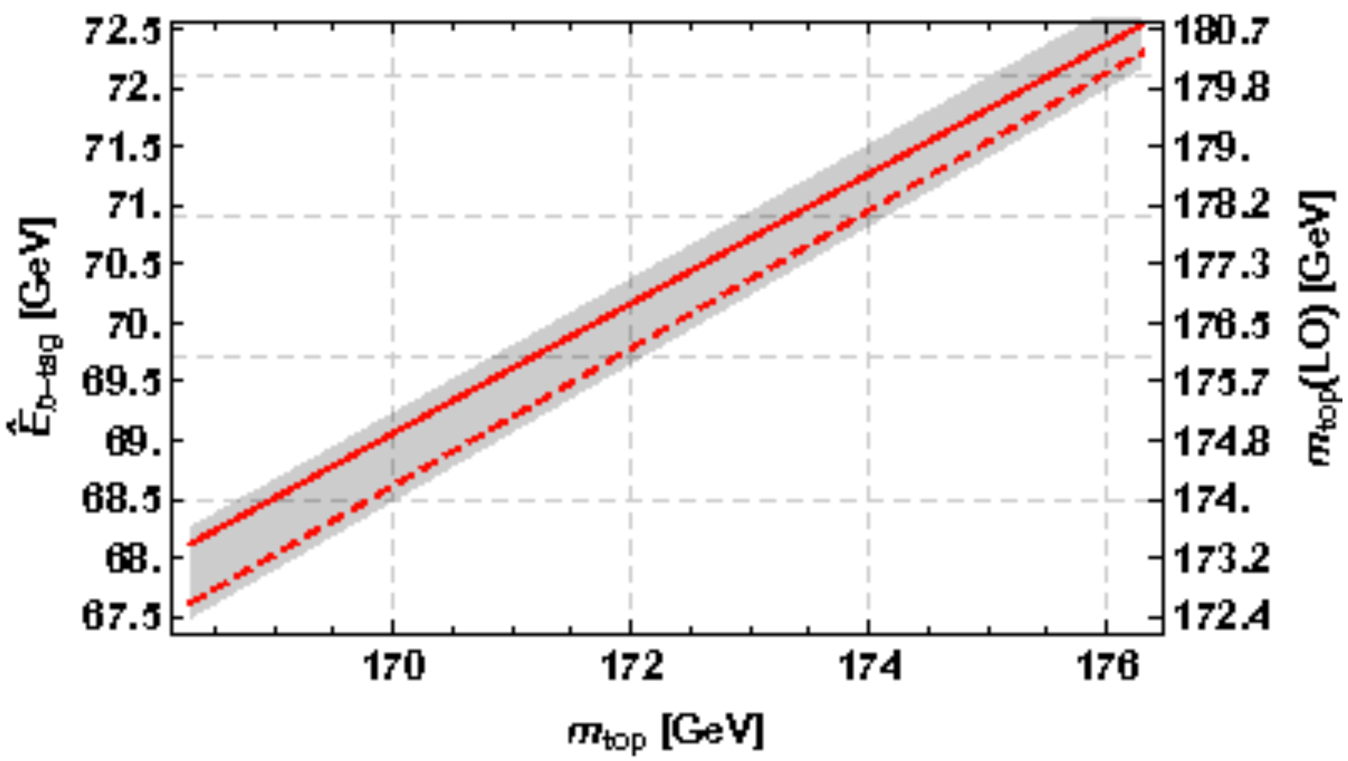
- Study 8 variables sensitive to color reconnections, ISR/FSR, b-quark kinematics.
- Measurement calibrated in each bin minus average from the inclusive measurement.
- *No indication of a kinematic bias.*
- *Statistics not yet enough to constrain further some of the alternate ttbar models.*

E. Yazgan

The top quark mass

A long-standing issue to figure out the numerical value of the top quark. This was successfully accomplished, and now we are trying to figure out what exactly has been actually measured...

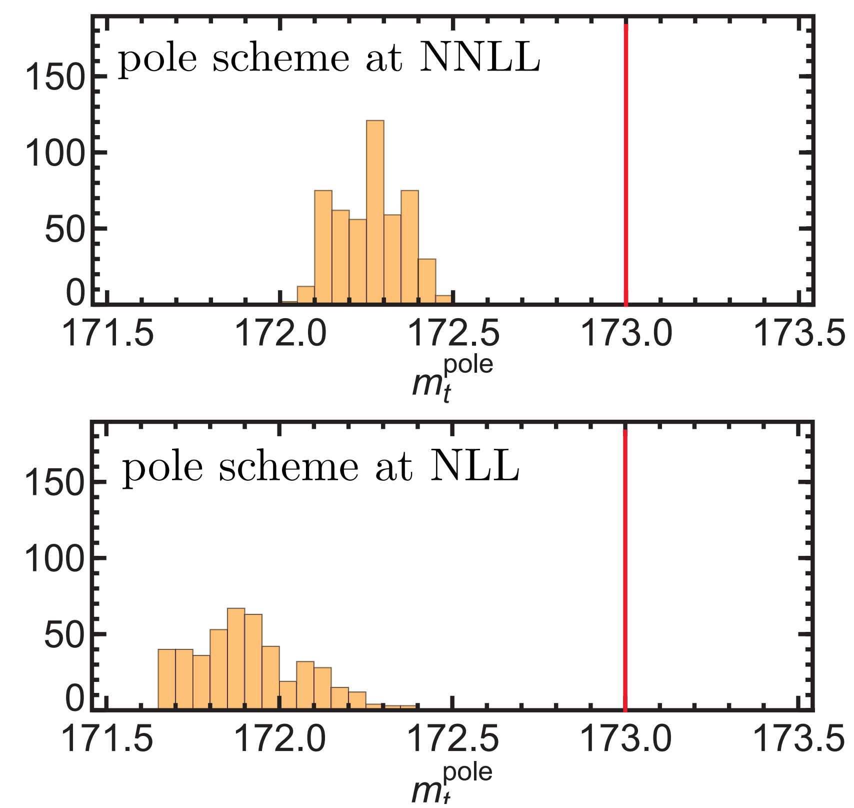
The position of the energy peak of the b-quark from top decay in the lab frame, is independent of collider energy, colliding particles etc.



For a 1% jet energy scale uncertainty (and assuming negligible statistical error), the top quark mass can then be extracted using the energy-peak of b-jets with an error +- (1.2 (exp) + 0.6(th)) GeV.

Franchensini

Pythia mass calibration using SCET: observed O(600) MeV difference between MC input and the observed value of the pole mass. MC mass is larger... The pole mass moves...



Butenschoen et al.

The W mass

Talks by Viccini, Schwinn, Martinez

It is expected that the W mass will be measured at the LHC with the uncertainty of about 5 MeV.... (0.5 %). This is an outstanding precision for the hadron collider; need to control many different aspects of hadron collisions to attain it.

Radiative corrections: QCD, EW, mixed-QCD electroweak.

Parton distribution functions.

Multiple photons.

- Continuous progress in DY studies: new analytical calculations ($O(\alpha\alpha_s)$ corrections)
  implementation of new codes (QCD, QCDxEW)

- The completion of the systematic comparison of DY simulation codes in arXiv:1606.02330
  - allows us to discuss the size of purely QCD and purely EW higher-order corrections
  - allows us to discuss on a solid ground the combination of QCD and EW corrections once the individual QCD and EW components are under control (cfr. the POWHEG exampl
  - the precise size of the mixed QCDxEW corrections depends on the formulation of the code, which can be understood also thanks to recent analytical progresses

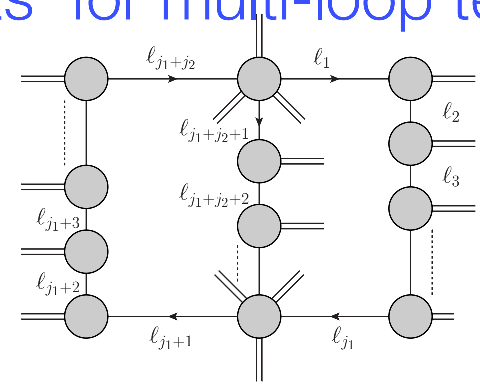
- The estimate of the theoretical uncertainties on MW, due to yet unknown corrections, is underway
  - it requires a clear definition of the set of observables that are simultaneously studied to perform a consistent QCD analysis
  - purely EW uncertainties on MW are small (beware of additional soft lepton pairs)
  - progress in the estimate of subleading $O(\alpha\alpha_s)$ (corrections and uncertainties)

There are three things that I did not talk about but it is easy to summarize them for you:

there is a permanent progress in multi-loop technology, steady-state of anomalies in B-physics, and never-ending confusion about the discovery of the quark gluon plasma....

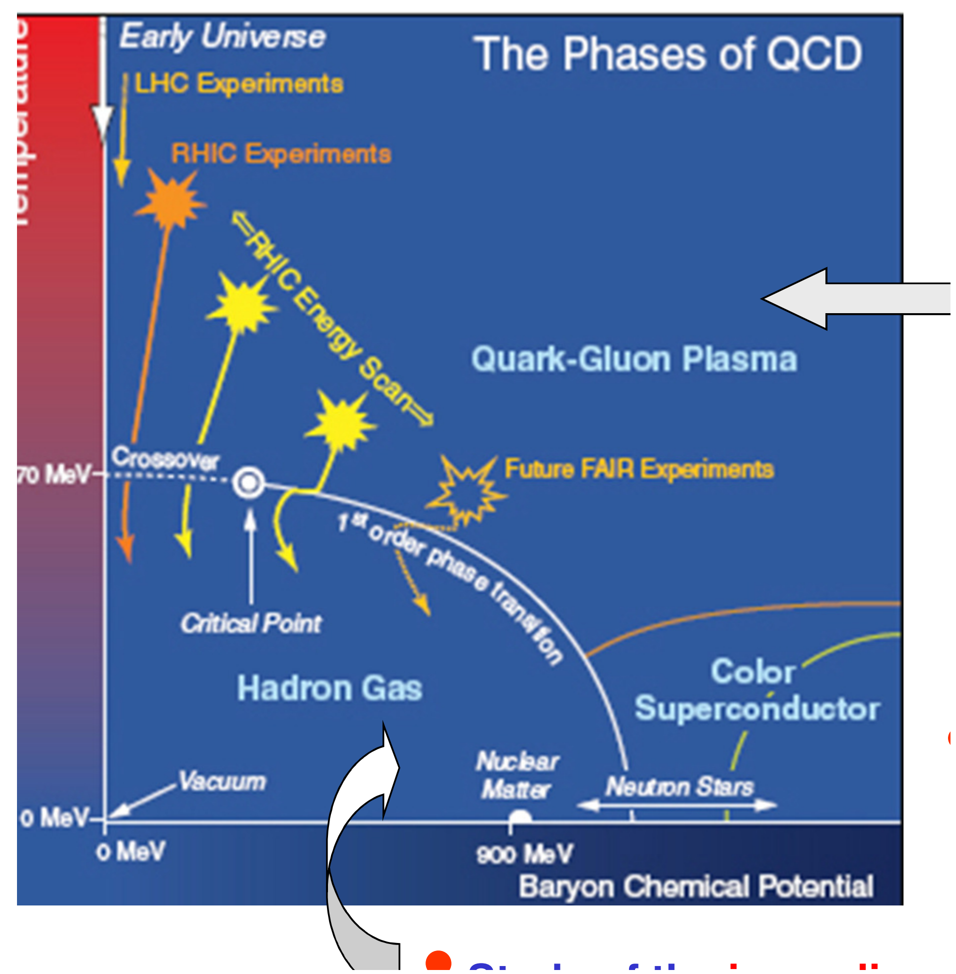
New ideas/results for multi-loop technology

Perano, Papadopoulos



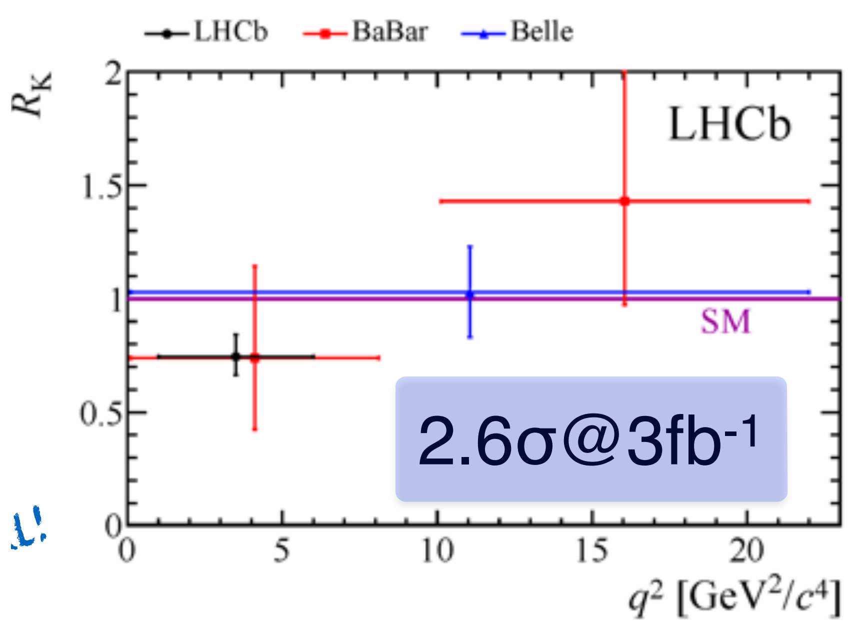
QCD at high density

Bratkovskaya



Heavy quarks **Zwicky**

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$



Thanks !

Many thanks to the participants for making this meeting interesting, informative and exciting!

Many thanks to the organizers for creating such a pleasant and inspiring atmosphere!