QCD instanton searches with forward proton tagging

Beam view: looking downstream through the beam pipe
at a fully inserted Roman pot

Marek Taševský

Institute of Physics, Czech Academy of Sciences, Prague

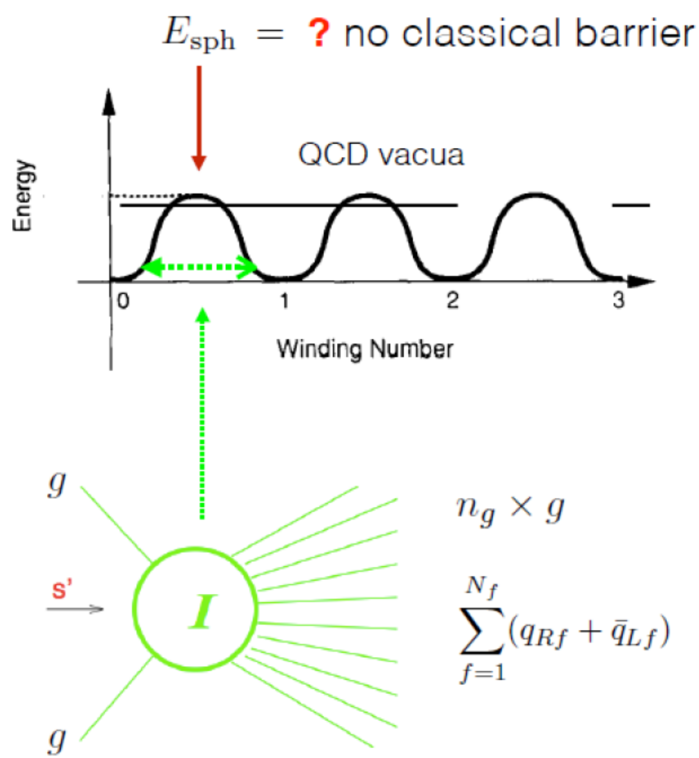
FZU Institute of Physics of the Czech Academy of Sciences

Instantons describe quantum tunneling between different vacuum sectors of the QCD and are arguably the best motivated yet experimentally unobserved nonperturbative effects predicted by the Standard Model.

Slide by Valery Khoze

QCD Instantons

- Yang-Mills vacuum has a nontrivial structure
- *Instantons* are tunnelling solutions between the vacua.
- At the classical level there is no barrier in QCD. The *sphaleron is a quantum effect*
- Transitions between the vacua change chirality (result of the ABJ anomaly).
- All light quark-anti-quark pairs must participate in the reaction
- Not described by perturbation theory.



Sphaleron-transition on top of an energy barrier

$$g + g \rightarrow n_g \times g + \sum_{f=1}^{N_f}(q_{Rf} + \bar{q}_{Lf})$$

2

Final state signatures

Slide by Valery Khoze

Instantons have never been observed **experimentally**, however, they are playing very important role in the theoretical models of confinement and chiral symmetry breaking

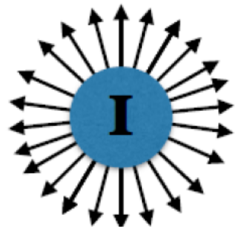
About 1800 titles

one of the biggest challenges for particle physics to date

a possible solution to the axial $U(1)$ problem

$< 0|G^a_{\mu\nu}G^a_{\mu\nu}|0 > \neq 0$

Instanton signatures:



LO Instanton vertex -> selection on final states at colliders with high sphericity

- large multiplicity $\quad N_{jet} \sim 1/\alpha_s(\rho_{inst}) \quad E_T \sim 1/\rho_{inst}$

'soft bombs' –high-multiplicity spherically symmetric distributions of relatively soft particles

- large 'Sphericity', $S \to 1$
- presence of an additional light $\bar{q}_R q_L$ pairs

(in particular pair of strange
(or charm, for the small size instanton) quarks)

Instanton$\neq$ the particle (no peak in M_{inst})
It is a family of objects of different size, ρ,
and orientations in Lorentz and colour spaces

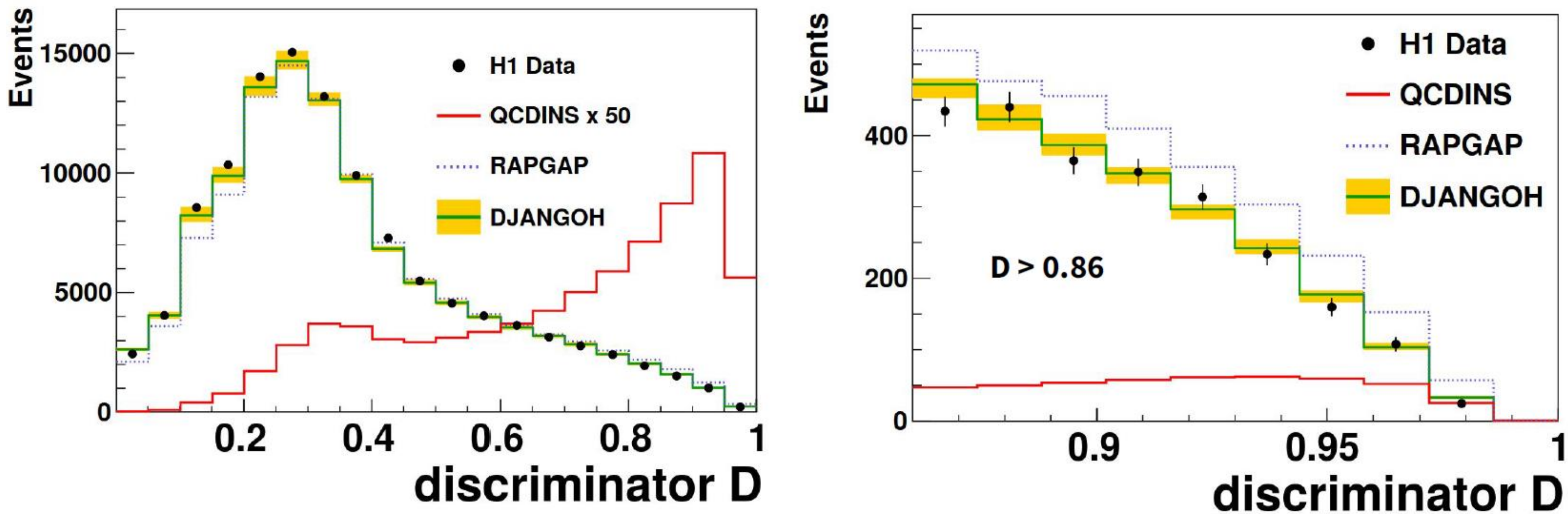
Extended objects in space-time

Effectively –a family of new multiparton vertices in Feynman diagrams

5

Instanton searches at HERA

By H1 Collaboration: EPJC 76 (2016) 7, 381



Evidence not found but predictions challenged for the first time

Calculations

Instanton-induced processes with 2 gluons in the initial state:

Slide by Valentin Khoze

All light flavours of quark-antiquark pairs must be present. Light =>

$$m_f \leq 1/\rho$$

instanton size

$$g + g \to n_g \times g + \sum_{f=1}^{N_f} (q_{Rf} + \bar{q}_{Lf})$$

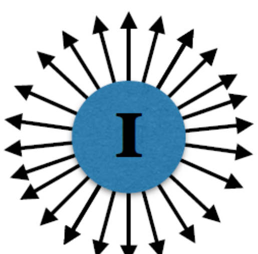
arbitrary (tends to be large ~1/alpha_s)

semiclassical suppression ('t Hooft) factor by the instanton action

$$S_I = \frac{8\pi^2}{g^2} = \frac{2\pi}{\alpha_s(\mu_r)}$$

$$\mathcal{A}_{2\to n_g+2N_f} \sim \int d^4x_0\, d\rho\, D(\rho)\, e^{-S_I} \left[\prod_{i=1}^{n_g+2} A^{a_i\,\mathrm{inst}}_{\mathrm{LSZ}}(p_i,\lambda_i)\right] \left[\prod_{j=1}^{2N_f} \psi^{(0)}_{\mathrm{LSZ}}(p_j,\lambda_j)\right]$$

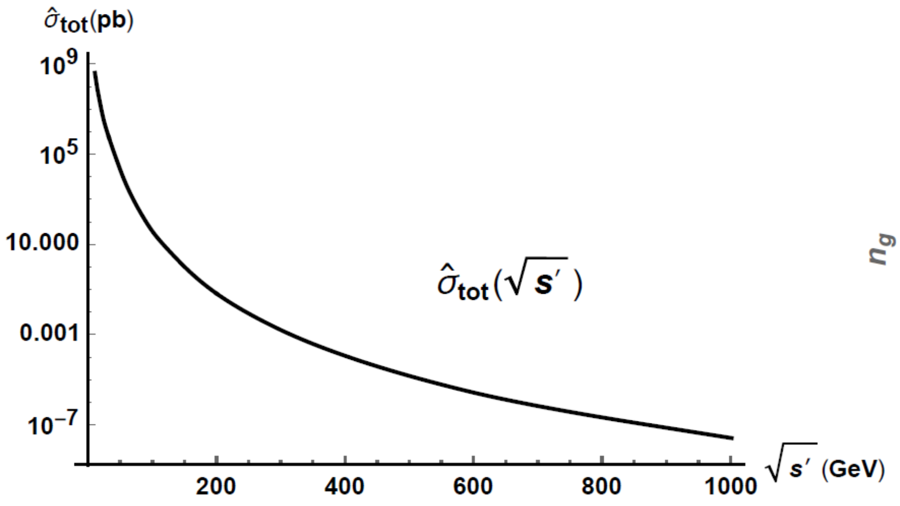
- the integrand: a product of bosonic and fermionic components of the instanton field configurations
- the factorised structure implies that emission of individual particles in the final state is uncorrelated and mutually independent.

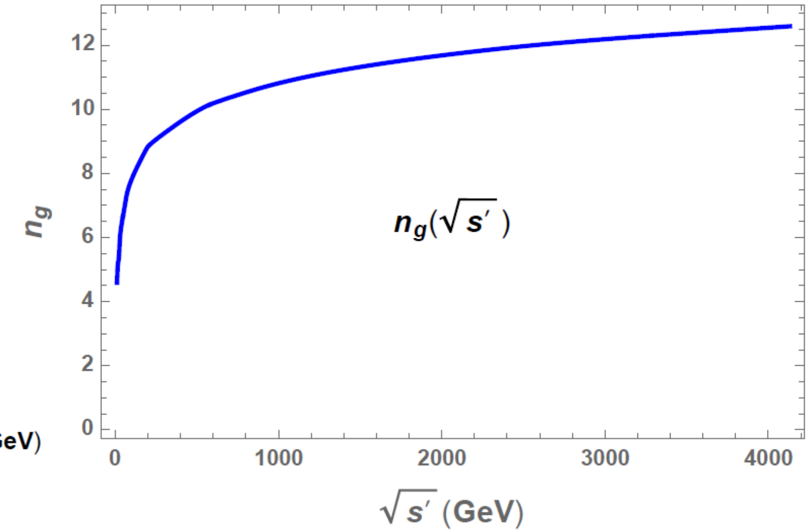


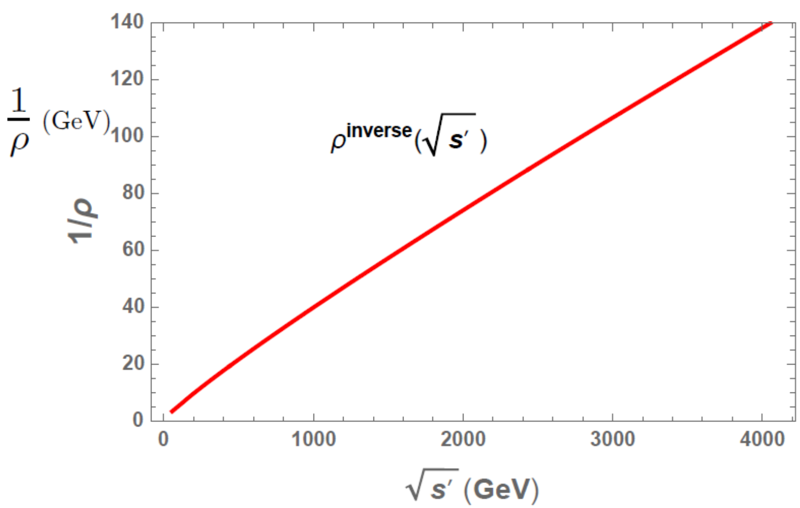
[this is correct at the LO in instanton pert. theory approximation]

LO Instanton vertex -> selection on final states at colliders with high sphericity

Theory predictions







VVKhoze, Kraus, Schott 1911.09726
VVKhoze, Milne, Spannovsky 2010.02287

- Small M_{inst} = large rates but difficult to distinguish from soft QCD (and pile-up)
- Large M_{inst} = striking multijet signature but low rates
- S/B decreases with increasing M_{inst}

→ Concentrate on low M_{inst}

Theory predictions

$\sqrt{\hat{s}}$ [GeV]	$\hat{\sigma}(gg \to X)$ [pb]	$\langle 1/\rho \rangle$ [GeV]	$\alpha_S(1/\rho)$	$\langle N_{\text{gluons}} \rangle$
20	2.01×10^6	1.69	0.327	7.81
25	9.49×10^5	1.98	0.306	8.58
30	4.64×10^5	2.27	0.290	9.07
35	2.32×10^5	2.52	0.279	9.61
40	1.25×10^5	2.84	0.267	9.67
50	3.89×10^4	3.38	0.251	10.56
60	1.38×10^4	3.87	0.241	10.89
70	5.45×10^3	4.33	0.232	11.38
80	2.36×10^3	4.85	0.224	11.67
90	1.08×10^3	5.24	0.219	12.31
100	5.44×10^2	5.82	0.213	12.10
110	2.79×10^2	6.21	0.209	12.62
120	1.53×10^2	6.71	0.205	12.77
130	8.56×10^1	7.13	0.201	13.04
140	4.99×10^1	7.57	0.198	13.25
150	3.01×10^1	8.00	0.195	13.45

Table. Partonic cross-section as a function of partonic centre-of-mass energy, $\sqrt{\hat{s}}$, taken from 2104.01861.

Theory predictions

Nominal factorisation scale choice, μ_F

Mass spectrum

Mean number of gluons to add to each event

$\sqrt{\hat{s}}$ [GeV]	$\hat{\sigma}(gg \to X)$ [pb]	$\langle 1/\rho \rangle$ [GeV]	$\alpha_S(1/\rho)$	$\langle N_{gluons} \rangle$
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Signal vs Background

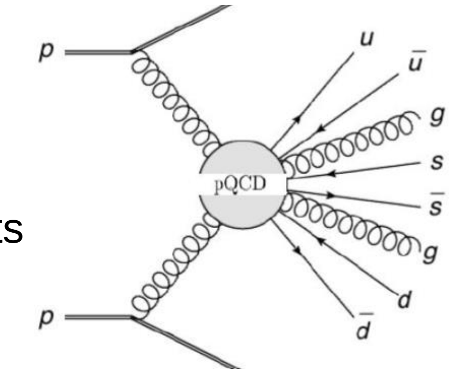
- **Instanton production** x-section falls with M_{inst} due to $\exp(-S_I) = \exp(-2\pi/\alpha_S(\varrho))$ in the amplitude.

$$\hat{\sigma}_{\text{inst}} \propto M_{\text{inst}}^{-6} \qquad M_{\text{inst}}^{-4}, \text{ at lower energies } 20 - 30 \text{ GeV}$$

Background 1: N minijets

Theory prediction for perturbatively formed hedgehog configuration of N minijets:

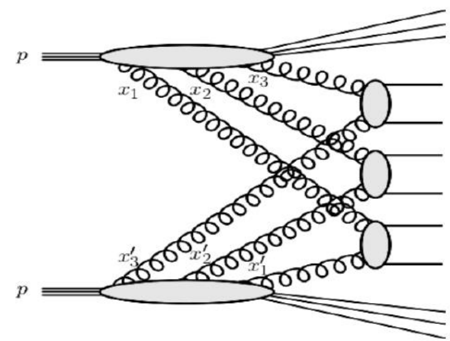
$$\sigma_{\text{pQCD}}(gg \to N \,\text{jets}) \sim \frac{16\pi}{M^2}\left(\frac{N_c}{\pi}\alpha_s(M)\right)^N$$ M=inv. mass of cluster of N minijets



→ from a certain value of M_{inst}, the signal becomes negligible wrt perturbative QCD
→ require M_{inst} < 200 GeV

Background 2: Multi-parton interactions

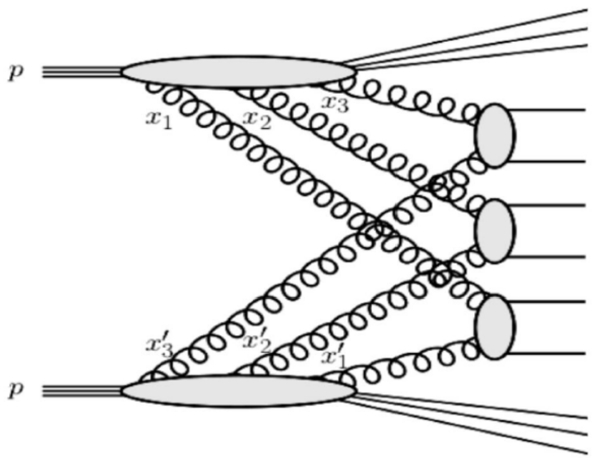
MPI final states also have high transverse sphericity
and dominate over signal for M_{inst} < 200 GeV



reach M_{inst} < 200 GeV and at the same time suppress MPI??

The main problem: multi-parton interactions

❑ **Inclusive searches:**
- Concentrate on low M_{inst} region
- main challenge: striking similarity between signal and MPI



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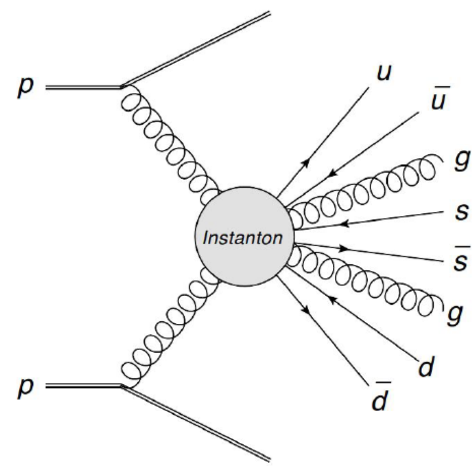

Minimum bias background ~ 110 mb

Signal ~ 200 pb

➢ Ongoing ATLAS analysis in the inclusive mode. Indeed challenging.

Signal vs Background

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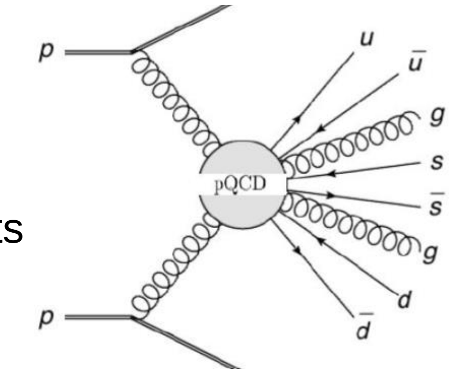

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→ from a certain value of M_{inst}, the signal becomes negligible wrt perturbative QCD
→ require M_{inst} < 200 GeV

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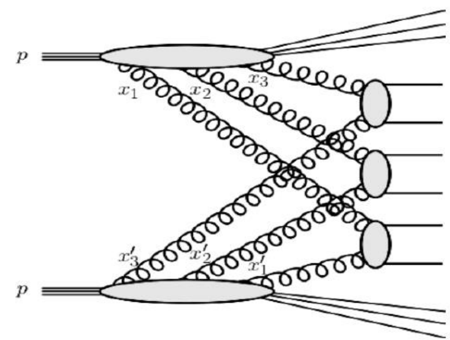
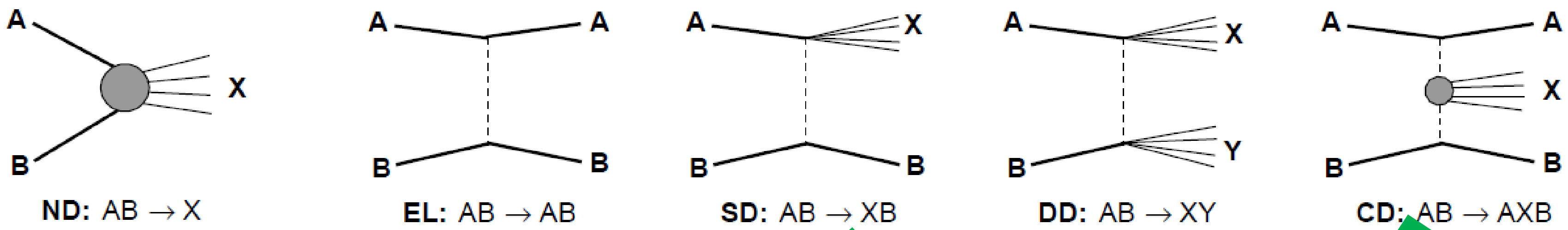


reach M_{inst} < 200 GeV and at the same time suppress MPI??

Go to final states with Large Rapidity Gap(s)!

Other production modes?



Inclusive production:

PLUS: signal x-section “large”
→ low instantaneous luminosities
are OK (pile-up not an issue)

MINUS: signal is mimicked by MB
background which has
a huge x-section

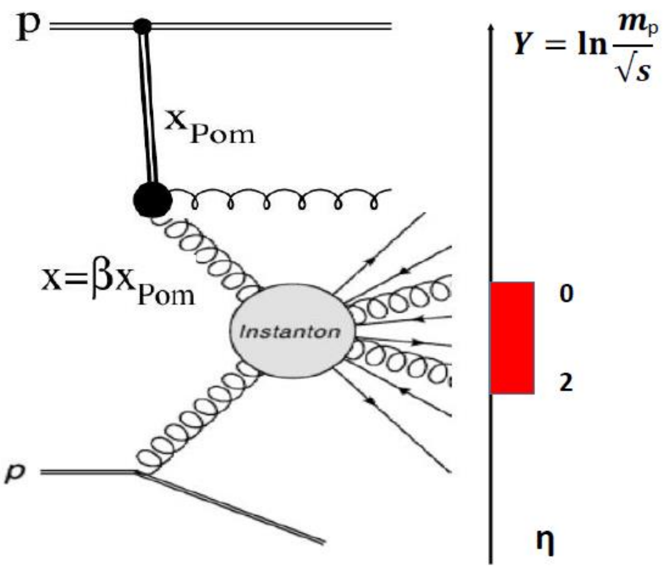
Pomeron exchange?

PLUS: much less parton radiation and MPI
in large rapidity gaps around intact protons

MINUS: signal x-section scaled by soft survival prob.
→ LRG is spoiled and larger instantaneous luminosities
are needed hence pile-up is an issue

Diffractively produced instantons

VVKhoze, VAKhoze, Milne, Ryskin 2104.01861



Effect of LRG studied at generator level

g+g → n_gx g + $\sum_{f=1}^{N_f}(q_{Rf}+q_{Lf})$:

Final state: multi-particle cluster containing a large number of isotropically distributed gluon (mini)jets accompanied by N_f light-quark jets

Event selection::

$N_{ch} > 20 \quad \sum_i E_{T,i} > 15$ **GeV**

$(0 < \eta < 2 \quad \mathbf{p}_{T,i} > 0.5$ **GeV**$)$

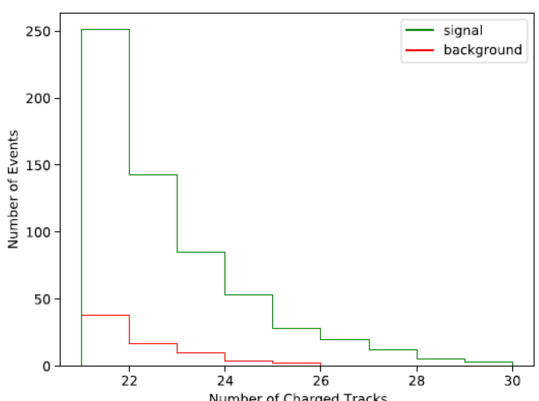
No charged at $-2 < \eta < 2$ **with** $p_T > 2$ **GeV**

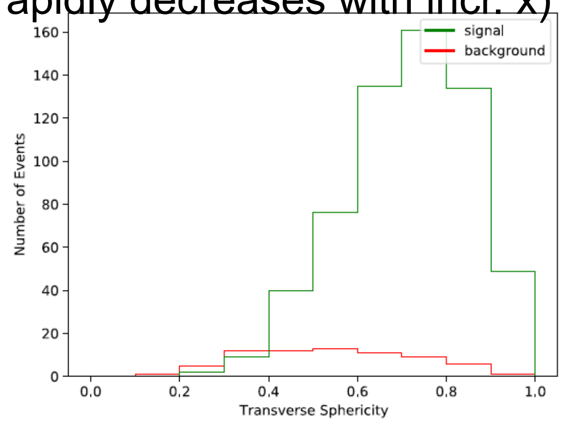
(to exclude high E_T **jets)**

ξ=0.003

Soft survival prob = 0.1 (=LRG)

Suppress gluons from Pomeron with too large x (where gPDF rapidly decreases with incr. x) → focus on 0<η<2



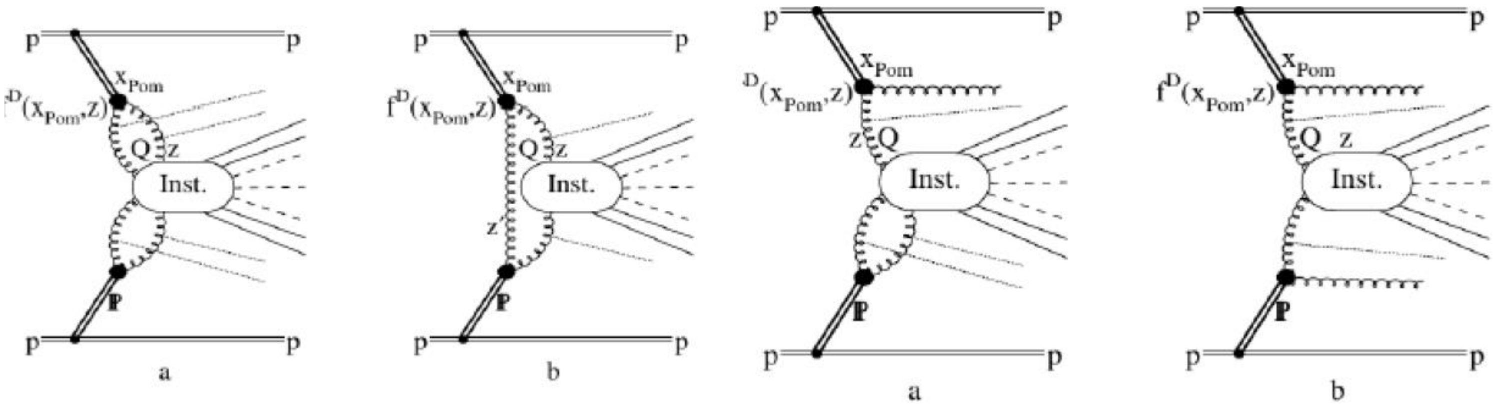


Main message:
S/B very good for
20 < M_{inst}< 60 GeV
but MPI not considered

Diffractively produced instantons

VVKhoze, VAKhoze, Milne, Ryskin 2111.02159

Central Instanton Production p+p → p+IP+IP+p → p+X+p

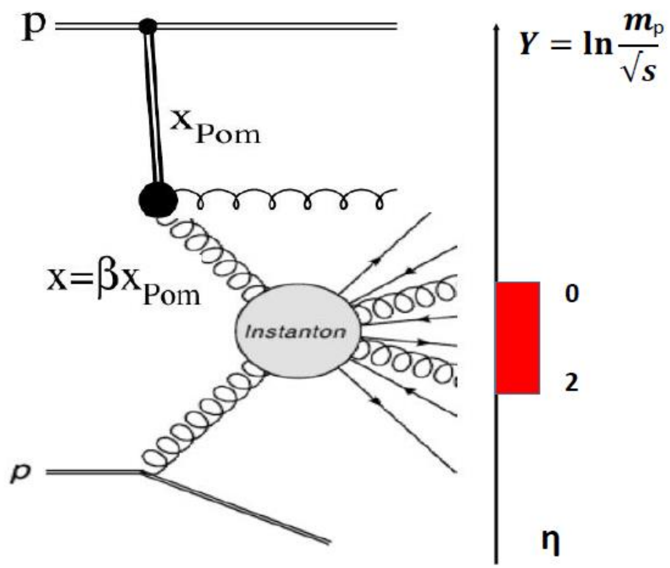


M_{inst} [GeV]	$d\sigma_{pp}^{(1a)}$[pb]	$d\sigma_{pp}^{(1b)}$[pb]	$d\sigma_{pp}^{(2a)}$[pb]	$d\sigma_{pp}^{(2b)}$[pb]	$d\sigma_{pp}^{(2b)}$, $Q_t > 20$GeV
15	13.3	$4.56{\cdot}10^{4}$	$3.72{\cdot}10^{3}$	$1.83{\cdot}10^{5}$	-
35	$6{\cdot}10^{-3}$	$1.69{\cdot}10^{2}$	8.10	$2.28{\cdot}10^{3}$	$1.99{\cdot}10^{-3}$
55	$3.82{\cdot}10^{-5}$	3.27	$1.19{\cdot}10^{-1}$	$8.96{\cdot}10^{1}$	$2.95{\cdot}10^{-3}$
75	$8.8{\cdot}10^{-7}$	$1.61{\cdot}10^{-1}$	$4.72{\cdot}10^{-3}$	7.06	$1.70{\cdot}10^{-3}$
95	$4.27{\cdot}10^{-8}$	$1.38{\cdot}10^{-2}$	$3.42{\cdot}10^{-4}$	$8.58{\cdot}10^{-1}$	$7.26{\cdot}10^{-4}$
115	$3.37{\cdot}10^{-9}$	$1.74{\cdot}10^{-3}$	$3.68{\cdot}10^{-5}$	$1.39{\cdot}10^{-1}$	$2.80{\cdot}10^{-4}$
135	$3.77{\cdot}10^{-10}$	$2.86{\cdot}10^{-4}$	$5.29{\cdot}10^{-6}$	$2.75{\cdot}10^{-2}$	$1.04{\cdot}10^{-4}$

For $\xi_1=\xi_2=0.03$

Predicted x-sections encouraging for a pure exclusive process or with an additional jet

Feasibility study for diffractive instantons



Tasevsky, VAKhoze, Milne, Ryskin 2208.14089

Look at Instanton produced in:

- ❑ Single-tagged process (Single Diffraction)
- ❑ Double-tagged processes (Central Diffraction)

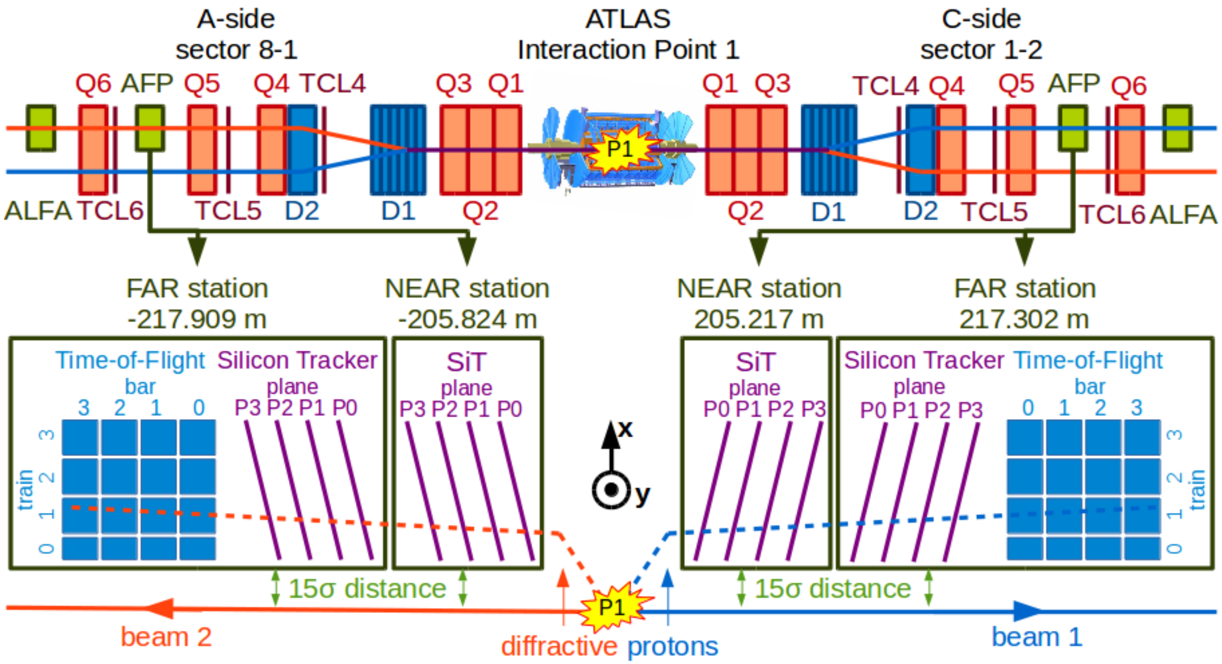
Focus on low 0.02<ξ<0.05 to suppress Reggeon exchanges and ND background

Significant extension of 2104.01861:

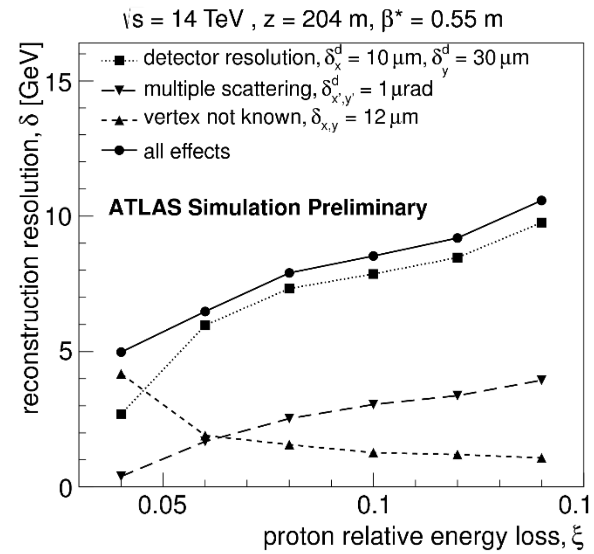
➢ Focus on 0<η<2 as well but rather than requiring LRG, require a proton tag (e.g. η<0) (experimentally requiring LRG necessitates zero pile-up → low signal event yields)
➢ Include MPI at particle level
➢ Include detector effects
➢ Include pile-up effects
➢ Concentrate on M_{inst}>60 GeV

And show what one can expect at detector level for four conceivable luminosity scenarios

Forward Proton detectors (FPDs) at LHC



AFP

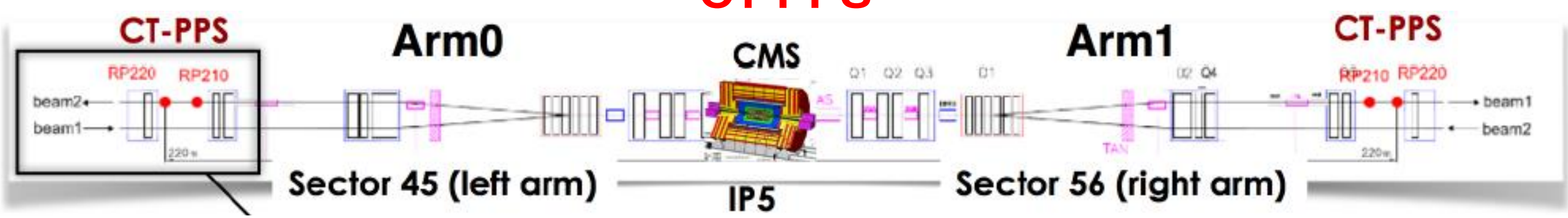


[AFP TDR, CERN-LHCC-2015-009]

$\xi_{1,2} = 1 - E_{proton1,2}/E_{beam}, \ \mathrm{M} = \sqrt{\xi_1 \xi_2 s}$

Excellent ξ (hence central system mass) resolution

CT-PPS



[CT-PPS TDR, CERN-LHCC-2014-021]

Search strategy: generator level

Tasevsky, VAKhoze, Milne, Ryskin 2208.14089

Variables used:

1) 0.02 < ξ < 0.05 – avoid large ξ to suppress

a) Reggeon contributions

b) ND background surviving thanks to fluctuations in the process of hadronization

2) N_{ch05} = nr. of charged particles with p_T>0.5 GeV and 0<η<2

3) $N_{ch20(25,30)}$ = nr. of charged particles with p_T>2.0 (2.5,3.0) GeV and 0<η<2

4) $\sum E_T$ over charged particles with p_T>0.5 GeV and 0<η<2

5) N_{chfw05} = nr. of charged particles with p_T>0.5 GeV and 2.5<η<4.9

6) $\sum E_T^{fw}$ over charged particles with p_T>0.5 GeV and 2.5<η<4.9

Cuts: N_{ch05} > 30, 40; $N_{ch20(25,30)}$ = 0; $\sum E_T$ > 30, 40 GeV; N_{chfw05} < 6; $\sum E_T^{fw}$ < 4 GeV

42 combinations tried → the golden cut scenario, giving the best S/B:

$$\boldsymbol{N_{ch05} > 40 \wedge N_{ch25} = 0 \wedge \sum E_T^{fw} < 4\ \text{GeV}}$$

Event generation

❑ Generator level:

Signal:

RAMBO event generator (author Valya Khoze) + hadronized by PYTHIA 8.2 (MPI on)

- SD (proton-Pomeron): M_{inst} > 60 GeV: 2.5M events: 1004.6 pb (for $0.02<\xi<0.05$)
- SD (proton-Pomeron): M_{inst} > 100 GeV: 0.5M events: 39.6 pb (for $0.02<\xi<0.05$)
- CD (Pomeron-Pomeron): M_{inst} > 100 GeV: 100k events: 0.5 pb (for $0.02<\xi_{1,2}<0.05$)

Background: jet production

PYTHIA 8.2: ISR on, FSR on, MPI on

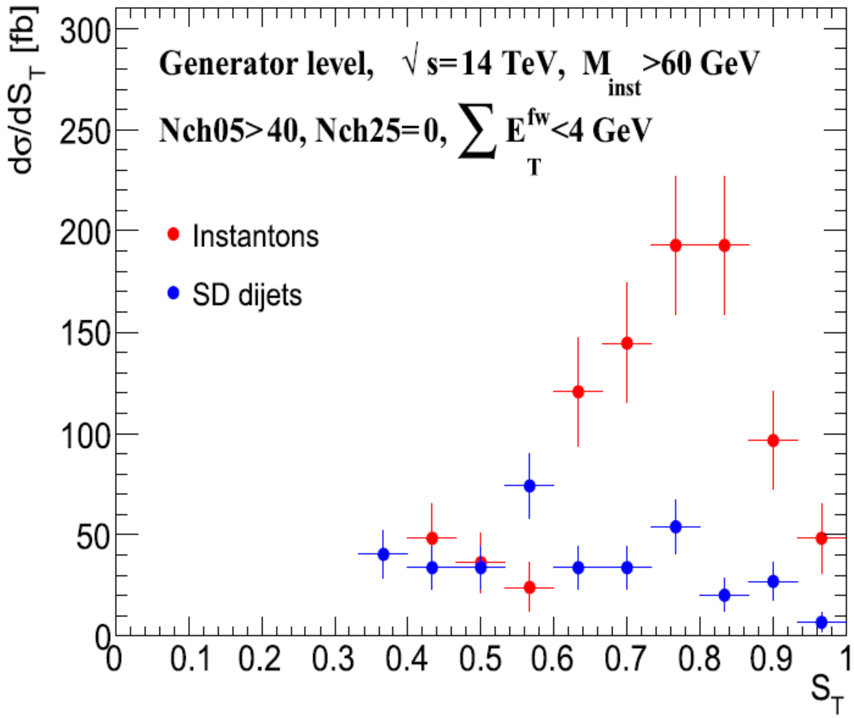
- SD: parton p_T > 10 GeV: 5.0x10^{11} events: 80 μb (dynamical gap generation)
- ND: parton p_T > 10 GeV: 8.5x10^{11} events: 8.6 mb

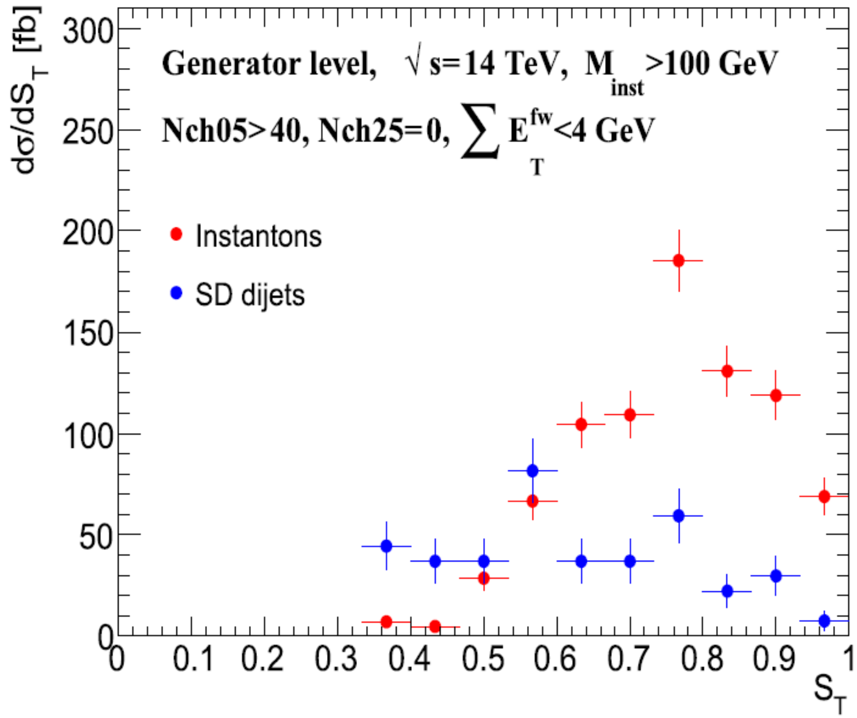
N_{ev} after golden cut scenario: SD: 455 → σ_{SD}^{fid}~73 fb;

ND: 0 → σ_{ND}^{fid} < 10.2 fb (< 14% of SD)

Single-tag: results at generator level

N_{ch05} **> 40 ∧** N_{ch25} **= 0 ∧** $\sum E_T^{fw}$ **< 4 GeV**





M_{inst} > 60 GeV: S/B = 2.3

Transverse sphericity

M_{inst} > 100 GeV: S/B = 2.1

Detector level

Detector effects and pile-up effects simulated using DELPHES 2.5

- Track selection: the same as in 13 TeV charged particle paper (EPJC76(2016) no 9, 502):
- $(z_{vtx}$-$z_{trk})$sinθ<1.5mm, d_0^{trk}<1.5mm → suppresses tracks from pile-up
- p_T>0.5 GeV and 0<η<2
- Nominal ATLAS track reco efficiency: ~80% for p_T>0.5 GeV, not too close to tracker edges: N_{ch05} > 40 → N_{tr05} > 32: adapt the first cut for detector level (Goal of this analysis is to estimate the situation after data taking, so real event yields)
- Adapt also the third cut: $\sum E_T^{fw}$ < 4 GeV → $\sum E_T^{fwcalo}$ < 5 GeV: increase the threshold (supported also by ATLAS Run 1 Energy flow paper) but not too much since no control over pile-up penetration
- The second cut is tightened to increase S/B

  $\boldsymbol{N_{tr05} > 25 \wedge N_{tr20} = 0 \wedge \sum E_T^{fwcalo} < 5}$ **GeV** for M_{inst} > 60 GeV

  $\boldsymbol{N_{tr05} > 30 \wedge N_{tr25} = 0 \wedge \sum E_T^{fwcalo} < 5}$ **GeV** for M_{inst} > 100 GeV
- All signal events simulated
- SD/ND background samples pre-selected (by cuts more relaxed than the golden scenario):
- Pre-selection cuts: N_{ch05} > 30 ∧ N_{ch30} = 0 ∧ $\sum E_T^{fw}$ < 6 GeV →
- Number of DELPHES-simulated events: SD: 0.1M, ND: 1.5M

- Four luminosity scenarios (<μ>, L[fb-1]): (0,0.1), (1,0.1), (2,1) and (5,10) for Single-tag ana
- Two luminosity scenarios (20,60) and (50,300) for Double-tag analysis

Detector level

- But S/B for the golden cut scenario adapted to det.level above drops from 2.3 (2.1) at gen. level to 0.6 (0.3) at det. level independently of the amount of pile-up → detector effects significant (track reco efficiencies and resolutions).

Apply this additional cut at det. level: ξ^{calo} **< 0.025.** It uses information from calorimeter, not from AFP!
It brings S/B to above 1.0 again.

- The final golden cut scenario at det.level:

N_{tr05} **> 25 ∧** N_{tr20} **= 0 ∧** $\sum E_T^{fwcalo}$ **< 5 GeV ∧** ξ^{calo} **< 0.025** for $M_{inst} >$ 60 GeV
N_{tr05} **> 30 ∧** N_{tr25} **= 0 ∧** $\sum E_T^{fwcalo}$ **< 5 GeV ∧** ξ^{calo} **< 0.025** for $M_{inst} >$ 100 GeV

Combinatorial background

- With increasing <μ>, the probability to detect a pile-up proton in AFP increases.

- Probability to see a proton from MB in the AFP acceptance 0.02<ξ<0.05 on one side: $\boldsymbol{P_{ST}}$**=0.005** (based on PYTHIA 8.2, softQCD=all, ISR on, FSR on, MPI on)

- For a given <μ>, probability per bunch crossing to see a proton in AFP on one side:
$P_{comb} = 1 - (1 - P_{ST})^{<\mu>}$

- Total combinatorial background:
Single-tag: $(\sigma_{SD}^{fid} + \sigma_{ND}^{fid})$*$P_{comb}$; P_{comb} = 0.5%, 1.0% and 2.4% for <μ>=1, 2 and 5, resp.

Double-tag: $(\sigma_{SD}^{fid} + \sigma_{ND}^{fid})$* P_{comb}^2; P_{comb}^2 = 0.8% and 4.6% for <μ>=20 and 50, resp.

NOTE: The cut 0.02<ξ<0.05 only applied to get P_{comb}, not on the hard-scale background process!

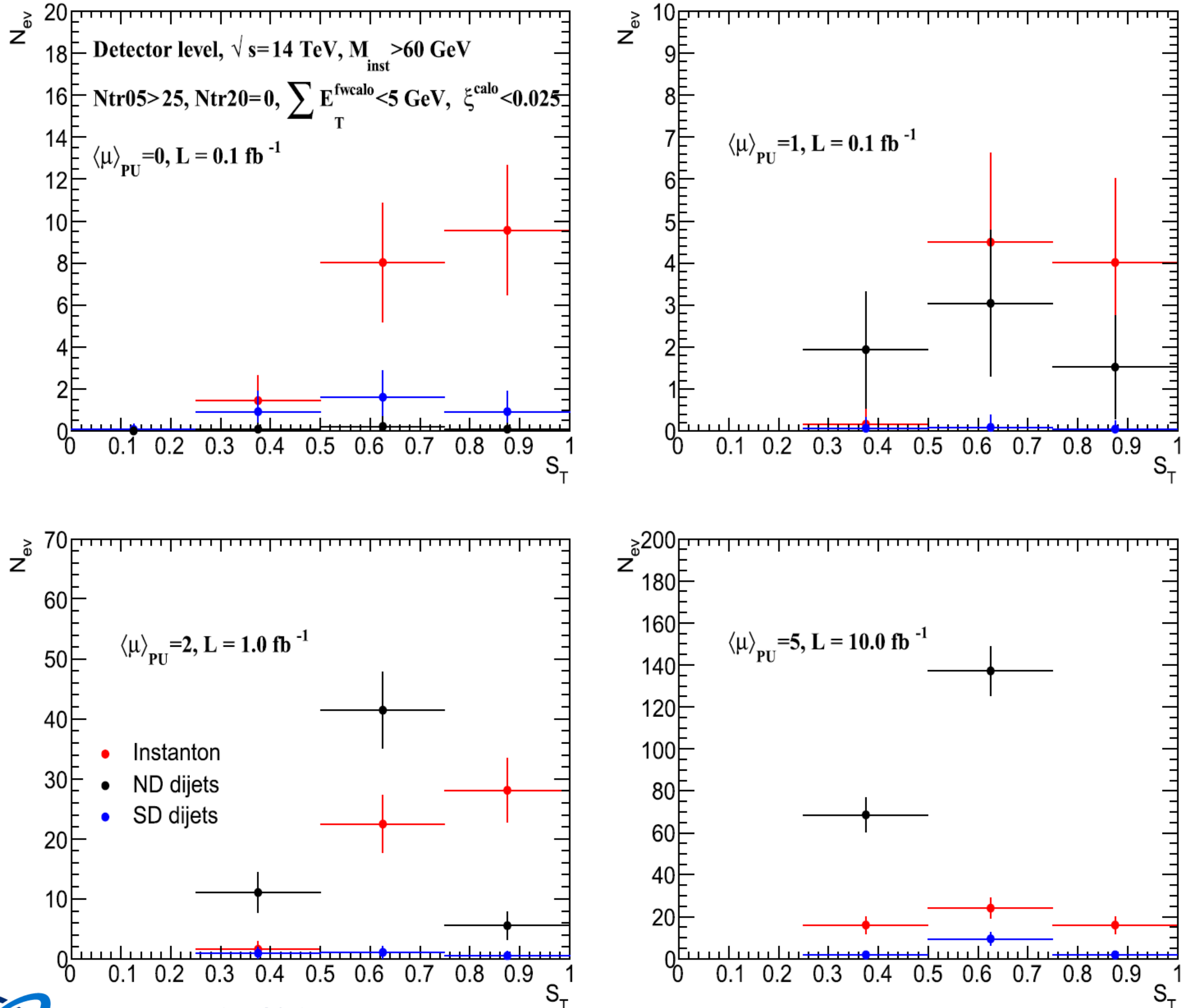
Both can be suppressed by ToF: 20 ps → by 9 (<μ>=20) and 8 (<μ>=50)

- Single-tagged analysis: combinatorial bg dominated by ND processes and increases with <μ>

- Double-tagged analysis: signal x-section for CD/SD ~ 1/80 → large integrated lumi are needed → large <μ> must be considered → combinatorial background overwhelming, even when suppressed using ToF detector.
For a similar golden cut scenario: S/B for ST to DT: 1/16 and ~1/100x for (20,60) and (50,300), resp.

Single-tag: results at detector level

$N_{tr05} > 25 \wedge N_{tr20} = 0 \wedge \sum E_T^{fwcalo} < 5\ \text{GeV} \wedge \xi^{calo} < 0.025$

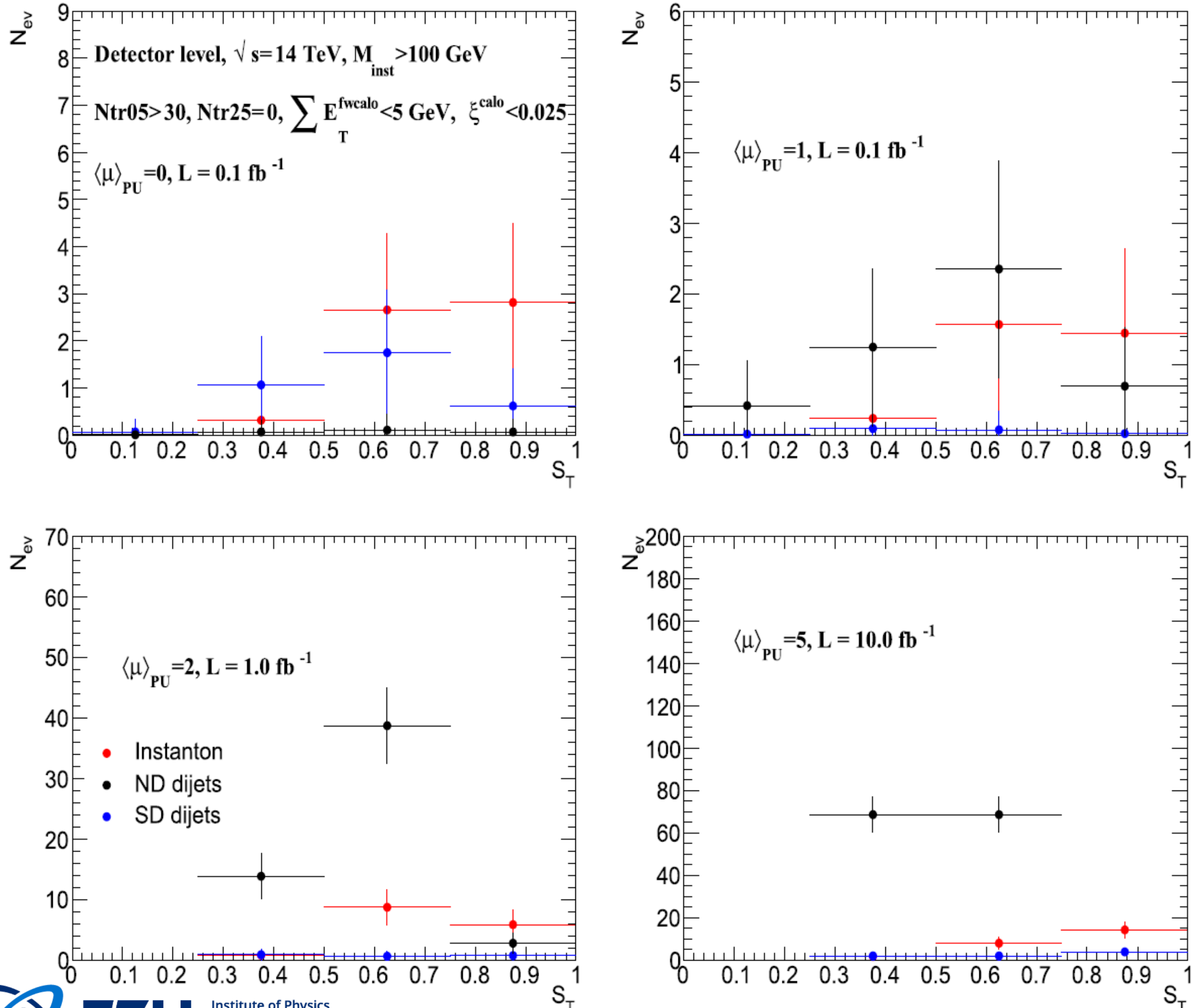


M_{inst} > 60 GeV

- Fast simulation of detector effects using DELPHES
- Pile-up effects included in signal as well as SD and ND backgrounds
- Four luminosity scenarios evaluated

Single-tag: results at detector level

$N_{tr05} > 30 \wedge N_{tr25} = 0 \wedge \sum E_T^{fwcalo} < 5$ GeV $\wedge\ \xi^{calo} < 0.025$



M_{inst} > 100 GeV

- Fast simulation of detector effects using DELPHES
- Pile-up effects included in signal as well as SD and ND backgrounds
- Four luminosity scenarios evaluated

Single-tag: event yields at detector level

$(\langle\mu\rangle, \mathcal{L}$ [fb^{-1}])	$M_{\rm inst} > 60$ GeV	$M_{\rm inst} > 100$ GeV
(0, 0.1)	19.0/(0.4+3.5)	5.8/(0.2+3.5)
(1.0, 0.1)	8.7/(6.5+0.2)	3.2/(4.7+0.2)
(2.0, 1.0)	52.2/(58.1+2.5)	15.4/(55.3+2.2)
(5.0, 10.0)	56.2/(205.6+13.3)	23.8/(137.1+7.6)

$N_S/(N_{SD}+N_{ND})$

Detector and pile-up effects included

Systematic studies ($M_{inst} > 60$ GeV):

- $\sum E_T^{fwcalo} < 6$ GeV: effect marginal
- Original tracking: $N_{tr05} > 26(27) \wedge N_{tr20} = 0 \wedge \sum E_T^{fwcalo} < 5$ GeV: similar S/B
- More efficient tracking: 80% → 90%: $N_{tr05} > 28(30) \wedge N_{tr20} = 0 \wedge \sum E_T^{fwcalo} < 5$ GeV: similar S/B

M_{inst}>100 GeV: $N_{tr05} > 35 \wedge N_{tr25} = 0 \wedge \sum E_T^{fwcalo} < 5$ GeV : S/B~1.5 for μ=0 but too few events

Common-ground working point (giving the same S/B for M_{inst}>60 and M_{inst}>100 GeV):

$N_{tr05} > 30 \wedge N_{tr20} = 0 \wedge \sum E_T^{fwcalo} < 5$ GeV: S/B ~ 0.4-0.7

Summary

Recent theory papers on searches for QCD instanton of low masses (20<M_{inst}<60 GeV) at LHC are encouraging.

Goal of this analysis is to extend the previous theory studies by:

- Considering higher masses (M_{inst} > 60 GeV, M_{inst} > 100 GeV)
- Including multi-parton interactions
- Including detector effects
- Including pile-up effects

Single-tag approach:
S/B ~ 2.3 (>60 GeV) or 2.1 (>100 GeV) at generator level deteriorate to S/B~0.6 or 0.3 at detector level.
Track reconstruction efficiencies and resolutions seem to be responsible.

➢ **After including more cuts, detector and pile-up effects kept under control and S/B above 1.0 for <μ> ≤ 1 and Lumi ~ 0.1fb-1.**

Double-tag approach:
Since signal production cross section is 80x smaller than for SD, we have to consider larger values of <μ> (20 and 50). There combinatorial effects are big and overwhelm the signal, even when suppressed by using ToF detector.

Potential improvements

1. Build an Instanton-dedicated L1 or higher-level trigger
2. Add time information to central or forward region
3. Number of c-quarks in Signal larger than in Backgrounds

BACKUP SLIDES

Notes from Valentin Khoze

- QCD instanton cross-sections can be very large at hadron colliders.

- Instanton events are isotropic multi-particle final states [in CoM frame]. Event topology is very distinct - can use transverse sphericity & jet broadening event shapes. Also can look for c-cbar pairs in final states.

- Particles with large pT emitted from the instanton are rare. Especially hard to produce them at low partonic energies (for obvious kinematic reasons). They do not pass hight-pT triggers.

- At large (partonic) energies [=> M_inst] instanton events can pass high-pT triggers but have hopelessly suppressed cross-sections.

- Alternative approach 1: Examine data collected with minimum bias trigger [so no high-pT triggers!]

- Alternative approach 2: + Consider instanton production in diffractive processes looking for final states with large rapidity gaps.